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CHAPTER 13

PLANT SALT TOLERANCE

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INTRODUCTION

As noted in previous chapters of this manual, the quality of irrigation water is an important factor in determining sustainability of agriculture on salt-impaired lands. For a number of reasons, the availability of low-salinity irrigation supplies has led to (1) an interest in using alternative supplies, such as recycled wastewaters, and (2) innovative plant and water management strategies to mitigate the adverse effects of salt and specific-ion stresses these poor-quality waters may impose on plant growth, yield, and quality. A second motivating factor is the lack of suitable drainage outlets in many agricultural areas of the world. Drainage of irrigated lands is one of the requisites for sustaining agricultural productivity in a given region over the long term. Adequate drainage not only allows for better aeration in the crop rootzone but provides a means by which salinity and toxic elements can be managed and controlled. Reuse of drainage water for irrigation is one way of expanding the useable water supply while at the same time reducing drainage volume. This chapter provides a management perspective on (1) how plants respond to salinity and toxic elements (e.g., Na^+ , Cl^- , and B); (2) crop salt tolerance and the various factors that influence plant response to salinity; (3) the extent to which salinity affects crop yields and quality; and (4) management strategies to optimize yields by controlling soil salinity. It is not our intent to provide a comprehensive review of physiological effects of salinity crops. That topic is covered in detail in Chapter 6.

SOURCE AND CAUSES OF SOIL SALINITY

Salts found in soils and waters originate from parent rock material that has undergone geochemical weathering. Over geologic time, primary minerals have reacted with water, oxygen, and carbon dioxide to form secondary minerals and salts that were transported by water to oceans or depressions in the landscape. Inundation of large land masses by saline seas deposited sedimentary materials that have become the major source of salt in arid regions.

In coastal or delta regions, salination of soils may occur predominantly by salts that contaminate freshwater supplies by seawater intrusion. Seawater intrusion can impair groundwater quality when wells are pumped to the extent that they overdraft aquifers near coastal areas. Salinity in freshwater channels near deltas is affected by the tide and can increase dramatically during high tides when stream flows are low. Coastal agriculture may also be subjected to cyclic salts where saline aerosols are produced by violent wave activity during storms or high winds on the sea. These salts can move inland considerable distances, but the most harmful effects occur on vegetation or crops grown close to the shore.

Salts, however, can be found in groundwater at relatively high concentrations without originating from the sea. The concentration and composition of groundwater is largely dependent on the hydrological and geochemical environment that the infiltrating water encounters en route to the groundwater. This is particularly true in irrigated soils formed from marine sediments. Salts contained in irrigation water, regardless of their source, can salinize agricultural land if the mass of salts that moves out of the rootzone is less than the mass of salts entering the rootzone for an extended period of time. A favorable salt balance within the rootzone must be maintained by adequate leaching.

In closed hydrologic basins, salts may have been present in the soil long before irrigation was introduced to a region. Upon irrigation, saline water tables can develop in poorly drained areas in relatively short time periods (i.e., years). Even if good-quality water is used for irrigation, salination may occur from capillary movement of salts and water to the surface from rising saline water tables. Rising water tables are a result of excessive deep percolation and are often associated with inefficient water-management practices, such as overirrigation or inadequate drainage systems.

The two processes described, (1) salination from irrigation with saline water, and (2) salination from shallow saline water tables, are the most common cause of large-scale soil salination in irrigated agriculture. They are, of course, not mutually exclusive, and highly saline water tables can often occur from or in association with saline irrigation water. Other processes of soil salination described in Chapter 1 occur on a smaller scale and will not be discussed in this section.

PLANT SALT TOLERANCE

Plant salt tolerance is defined differently depending on the intended use and value of the plant. For agricultural and horticultural crops, growers are most concerned with achieving economic yield and quality under saline conditions. For landscape designers and managers, the ability of the plant to maintain an aesthetic quality without excessive growth is of primary concern. And for the ecologist, the interest is most often on plant survival and species dominance in an environmentally sensitive area affected by salinity. Therefore, no one definition is appropriate that covers all interest groups.

Relative Yield–Response Curves for Agronomic and Horticultural Crops

The salt tolerance of a crop can be described as a complex function of yield decline across a range of salt concentrations (Maas and Hoffman 1977; Maas and Grattan 1999; van Genuchten and Hoffman 1984). Salt tolerance can be adequately described on the basis of two parameters: threshold, the electrical conductivity (EC_e) that is expected to cause the initial significant reduction in the maximum expected yield, and slope, the percentage of expected yield reduction per unit increase in salinity above the threshold value.

There is considerable uncertainty regarding the yield-threshold soil-salinity values. The salinity coefficients (yield threshold and slope values) for the piece-wise linear slope-threshold model introduced by Maas and Hoffman (1977) are now determined by nonlinear least-squares statistical fitting that determines the slope and threshold values from a particular experimental dataset. Despite intense control of salinity and all other important variables related to plant yield in salt tolerance trials, for many crops the standard errors associated with the threshold values can be 50% to 100% percent of the best-fit threshold value. Salinity studies on rice grown in northern California, for example, resulted in a threshold value of 1.9 dS/m of the field water (Grattan et al. 2002) with a 95% confidence limit ranging between 0.6 and 3.2 dS/m (J. Poss, U.S. Salinity Laboratory, personal communication, 2004). Obviously, very large ranges of uncertainty exist and additional studies to resolve this theoretical maximum are needed to refine water quality standards to a greater degree of confidence.

One approach recently described by Steppuhn et al. (2005a,b) substitutes a nonlinear relationship between relative yield and soil salinity similar to the nonlinear model introduced by van Genuchten and Hoffman (1984) for the linear “yield threshold” model. A curvilinear relationship better describes relative crop yield data than does the yield-threshold

expression. In this curvilinear relationship, there is no longer a “yield threshold” but, rather, a continuous decline in yield with increased soil salinity.

Using nonlinear models, the numerically most reliable curve-fitting parameter seems to be the value at which yield is reduced by 50% (C_{50}). The C_{50} value can still be estimated when too few data points exist to provide reliable information on the threshold and slope. The set of equations developed by van Genuchten and Hoffman (1984) takes advantage of the stability of C_{50} . The C_{50} value, together with a response curve steepness constant (p), may be obtained by fitting the appropriate function (van Genuchten 1983) to observed salt tolerance response data (van Genuchten and Gupta 1993). This approach has been used to develop a salt tolerance index (ST-index) as a revised indicator of the inherent salinity tolerance or resistance of agricultural crops to rootzone salinity (Steppuhn et al. 2005a,b).

Both nonlinear models as well as the piece-wise linear fit (Maas and Hoffman 1977) describe the data extremely well ($r^2 > 0.9$) (Steppuhn et al. 2005a,b). Water quality regulators prefer the latter since the concept of a “threshold” value provides them with a regulatory limit to impose on wastewater dischargers. The former, however, may best describe plant response from a physiological perspective, but there remains some uncertainty regarding the method that best describes the data in the relative yield range of 100% to 80%, the range of interest to most users and regulators. Since both curve-fitting methods describe the data well, we choose to report the most comprehensive and historically familiar list of salinity coefficients for the Maas-Hoffman model since this chapter is written as a user’s manual.

Herbaceous crops

Table 13-1 lists threshold and slope values generated by the Maas-Hoffman model for 81 crops in terms of seasonal average EC_e in the crop rootzone. Most of the data were obtained where crops were grown under conditions simulating recommended cultural and management practices for commercial production in the location tested. Consequently, the data indicate relative tolerances of different crops grown under different conditions and not under some standardized set of conditions. Furthermore, the data apply only where crops are exposed to fairly uniform salinities from the late seedling stage to maturity. Plants are likely to be more sensitive to salinity than the tables indicate should crops be planted in initially high-salinity conditions. Where crops have particularly sensitive stages, the tolerance limits are given in the footnotes.

The data in Table 13-1 apply to soils where chloride (Cl) is the predominant anion. Because of the dissolution of $CaSO_4$ when preparing saturated-soil extracts, the EC_e of gypsumiferous, (nonsodic, low Mg^{2+}) soils will

TABLE 13-1. Salt Tolerance of Herbaceous Crops^a

Crop			Salt-Tolerance Parameters		
Common Name (1)	Botanical Name ^b (2)	Tolerance Based On: (3)	Threshold ^c (EC _e) (dS/m) (4)	Slope (% per dS/m) (5)	Rating ^d (6)
<i>Fiber, grain, and special crops</i>					
Artichoke, Jerusalem	<i>Helianthus tuberosus</i> L.	Tuber yield	0.4	9.6	MS
Barley ^e	<i>Hordeum vulgare</i> L.	Grain yield	8.0	5.0	T
Canola or rapeseed	<i>Brassica campestris</i> L. [syn. <i>B. rapa</i> L.]	Seed yield	9.7	14	T
Canola or rapeseed	<i>B. napus</i> L.	Seed yield	11.0	13	T
Chick pea	<i>Cicer arietinum</i> L.	Seed yield	—	—	MS
Corn ^h	<i>Zea mays</i> L.	Ear FW	1.7	12	MS
Cotton	<i>Gossypium hirsutum</i> L.	Seed yield	7.7	5.2	T
Crambe	<i>Crambe abyssinica</i> Hochst. ex R.E. Fries	Seed yield	2.0	6.5	MS
Flax	<i>Linum usitatissimum</i> L.	Seed yield	1.7	12	MS
Guar	<i>Cyamopsis tetragonoloba</i> (L.) Taub.	Seed yield	8.8	17	T
Kenaf	<i>Hibiscus cannabinus</i> L.	Stem DW	8.1	11.6	T
Lesquerella	<i>Lesquerella fenderli</i> (Gray) S. Wats.	Seed yield	6.1	19	MT
Millet, channel	<i>Echinochloa turnerana</i> (Domin) J.M. Black	Grain yield	—	—	T
Oats	<i>Avena sativa</i> L.	Grain yield	—	—	T
Peanut	<i>Arachis hypogaea</i> L.	Seed yield	3.2	29	MS
Rice, paddy	<i>Oryza sativa</i> L.	Grain yield	3.0 ⁱ	12 ⁱ	S
Roselle	<i>Hibiscus sabdariffa</i> L.	Stem DW	—	—	MT
Rye	<i>Secale cereale</i> L.	Grain yield	11.4	10.8	T
Safflower	<i>Carthamus tinctorius</i> L.	Seed yield	—	—	MT
Sesame ^j	<i>Sesamum indicum</i> L.	Pod DW	—	—	S
Sorghum	<i>Sorghum bicolor</i> (L.) Moench	Grain yield	6.8	16	MT
Soybean	<i>Glycine max</i> (L.) Merrill	Seed yield	5.0	20	MT
Sugarbeet ^k	<i>Beta vulgaris</i> L.	Storage root	7.0	5.9	T

(continued)

TABLE 13-1. Salt Tolerance of Herbaceous Crops^a (Continued)

Crop			Salt-Tolerance Parameters		
Common Name (1)	Botanical Name ^b (2)	Tolerance Based On: (3)	Threshold ^c (EC _e) (dS/m) (4)	Slope (% per dS/m) (5)	Rating ^d (6)
Sugarcane	<i>Saccharum officinarum</i> L.	Shoot DW	1.7	5.9	MS
Sunflower	<i>Helianthus annuus</i> L.	Seed yield	4.8	5.0	MT
Triticale	<i>X Triticosecale</i> Wittmack	Grain yield	6.1	2.5	T
Wheat	<i>Triticum aestivum</i> L.	Grain yield	6.0	7.1	MT
Wheat (semidwarf) ^{f,a}	<i>T. aestivum</i> L.	Grain yield	8.6	3.0	T
Wheat, Durum	<i>T. turgidum</i> L. var. <i>durum</i> Desf.	Grain yield	5.9	3.8	T
<i>Grasses and forage crops</i>					
Alfalfa	<i>Medicago sativa</i> L.	Shoot DW	2.0	7.3	MS
Alkaligrass, Nuttall	<i>Puccinellia airoides</i> (Nutt.) Wats. & Coult.	Shoot DW	—	—	T*
Alkali sacaton	<i>Sporobolus airoides</i> Torr.	Shoot DW	—	—	T*
Barley (forage)	<i>Hordeum vulgare</i> L.	Shoot DW	6.0	7.1	MT
Bentgrass, creeping	<i>Agrostis stolonifera</i> L.	Shoot DW	—	—	MS
Bermudagrass ^m	<i>Cynodon dactylon</i> (L.) Pers.	Shoot DW	6.9	6.4	T
Bluestem, Angleton	<i>Dichanthium aristatum</i> (Poir.) C.E. Hubb. [syn. <i>Andropogon nodosus</i> (Willem.) Nash]	Shoot DW	—	—	MS*
Broadbean	<i>Vicia faba</i> L.	Shoot DW	1.6	9.6	MS
Brome, mountain	<i>Bromus marginatus</i> Nees ex Steud.	Shoot DW	—	—	MT*
Brome, smooth	<i>B. inermis</i> Leyss	Shoot DW	—	—	MT
Buffelgrass	<i>Pennisetum ciliare</i> (L.) Link. [syn. <i>Cenchrus ciliaris</i>]	Shoot DW	—	—	MS*
Burnet	<i>Poterium sanguisorba</i> L.	Shoot DW	—	—	MS*
Canarygrass, reed	<i>Phalaris arundinacea</i> L.	Shoot DW	—	—	MT
Clover, alsike	<i>Trifolium hybridum</i> L.	Shoot DW	1.5	12	MS
Clover, Berseem	<i>T. alexandrinum</i> L.	Shoot DW	1.5	5.7	MS

Clover, Hubam	<i>Melilotus alba</i> Dest. var. <i>annua</i> H.S.Coe	Shoot DW	—	—	MT*
Clover, ladino	<i>Trifolium repens</i> L.	Shoot DW	1.5	12	MS
Clover, Persian	<i>T. resupinatum</i> L.	Shoot DW	—	—	MS*
Clover, red	<i>T. pratense</i> L.	Shoot DW	1.5	12	MS
Clover, strawberry	<i>T. fragiferum</i> L.	Shoot DW	1.5	12	MS
Clover, sweet	<i>Melilotus</i> sp. Mill.	Shoot DW	—	—	MT*
Clover, white Dutch	<i>Trifolium repens</i> L.	Shoot DW	—	—	MS*
Corn (forage) ^f	<i>Zea mays</i> L.	Shoot DW	1.8	7.4	MS
Cowpea (forage)	<i>Vigna unguiculata</i> (L.) Walp.	Shoot DW	2.5	11	MS
Dallisgrass	<i>Paspalum dilatatum</i> Poir.	Shoot DW	—	—	MS*
Dhaincha	<i>Sesbania bispinosa</i> (Linn.) W.F. Wight [syn. <i>Sesbania aculeata</i> (Willd.) Poir]	Shoot DW	—	—	MT
Fescue, tall	<i>Festuca elatior</i> L.	Shoot DW	3.9	5.3	MT
Fescue, meadow	<i>Festuca pratensis</i> Huds.	Shoot DW	—	—	MT*
Foxtail, meadow	<i>Alopecurus pratensis</i> L.	Shoot DW	1.5	9.6	MS
Glycine	<i>Neonotonia wightii</i> [syn. <i>Glycine wightii</i> or <i>javanica</i>]	Shoot DW	—	—	MS
Gram, black or Urd bean	<i>Vigna mungo</i> (L.) Hepper [syn. <i>Phaseolus</i> <i>mungo</i> L.]	Shoot DW	—	—	S
Grama, blue	<i>Bouteloua gracilis</i> (HBK) Lag. ex Steud.	Shoot DW	—	—	MS*
Guinea grass	<i>Panicum maximum</i> Jacq.	Shoot DW	—	—	MT
Hardinggrass	<i>Phalaris tuberosa</i> L. var. <i>stenoptera</i> (Hack) A. S. Hitchc.	Shoot DW	4.6	7.6	MT
Kallargrass	<i>Leptochloa fusca</i> (L.) Kunth [syn. <i>Diplachne</i> <i>fusca</i> Beauv.]	Shoot DW	—	—	T
Kikuyugrass	<i>Pennisetum clandestinum</i> L.	Shoot DW	8.0	—	T
Lablab bean	<i>Lablab purpureus</i> (L.) Sweet [syn. <i>Dolichos</i> <i>lablab</i> L.]	Shoot DW	—	—	MS
Lovegrass ⁿ	<i>Eragrostis</i> sp. N. M. Wolf	Shoot DW	2.0	8.4	MS
Milkvetch, Cicer	<i>Astragalus cicer</i> L.	Shoot DW	—	—	MS*
Millet, Foxtail	<i>Setaria italica</i> (L.) Beauvois	Dry matter	—	—	MS

(continued)

TABLE 13-1. Salt Tolerance of Herbaceous Crops^a (Continued)

Crop			Salt-Tolerance Parameters		
Common Name (1)	Botanical Name ^b (2)	Tolerance Based On: (3)	Threshold ^c (EC _e) (dS/m) (4)	Slope (% per dS/m) (5)	Rating ^d (6)
Oatgrass, tall	<i>Arrhenatherum elatius</i> (L.) Beauvois ex J. Presl & K. Presl	Shoot DW	—	—	MS*
Oats (forage)	<i>Avena sativa</i> L.	Straw DW	—	—	T
Orchardgrass	<i>Dactylis glomerata</i> L.	Shoot DW	1.5	6.2	MS
Panicum, Blue	<i>Panicum antidotale</i> Retz.	Shoot DW	—	—	MS*
Pea, Pigeon	<i>Cajanus cajan</i> (L.) Huth [syn. <i>C. indicus</i> (K.) Spreng.]	Shoot DW	—	—	S
Rape (forage)	<i>Brassica napus</i> L.		—	—	MT*
Rescuegrass	<i>Bromus unioloides</i> HBK	Shoot DW	—	—	MT*
Rhodesgrass	<i>Chloris Gayana</i> Kunth.	Shoot DW	—	—	MT
Rye (forage)	<i>Secale cereale</i> L.	Shoot DW	7.6	4.9	T
Ryegrass, Italian	<i>Lolium multiflorum</i> Lam.	Shoot DW	—	—	MT*
Ryegrass, perennial	<i>Lolium perenne</i> L.	Shoot DW	5.6	7.6	MT
Ryegrass, Wimmera	<i>L. rigidum</i> Gaud.		—	—	MT*
Salt grass, desert	<i>Distichlis spicata</i> L. var. <i>stricta</i> (Torr.) Bettle	Shoot DW	—	—	T*
Sesbania	<i>Sesbania exaltata</i> (Raf.) V.L. Cory	Shoot DW	2.3	7.0	MS
Sirato	<i>Macroptilium atropurpureum</i> (DC.) Urb.	Shoot DW	—	—	MS
Sphaerophysa	<i>Sphaerophysa salsula</i> (Pall.) DC	Shoot DW	2.2	7.0	MS
Sudangrass	<i>Sorghum sudanense</i> (Piper) Stapf	Shoot DW	2.8	4.3	MT
Timothy	<i>Phleum pratense</i> L.	Shoot DW	—	—	MS*
Trefoil, big	<i>Lotus pedunculatus</i> Cav.	Shoot DW	2.3	19	MS
Trefoil, narrowleaf birdsfoot	<i>L. corniculatus</i> var. <i>tenuifolium</i> L.	Shoot DW	5.0	10	MT
Trefoil, broadleaf birdsfoot	<i>L. corniculatus</i> L. var. <i>arvensis</i> (Schkuhr) Ser. ex DC	Shoot DW	—	—	MS

Vetch, common	<i>Vicia angustifolia</i> L.	Shoot DW	3.0	11	MS
Wheat (forage) ^l	<i>Triticum aestivum</i> L.	Shoot DW	4.5	2.6	MT
Wheat, Durum (forage)	<i>T. turgidum</i> L. var <i>durum</i> Desf.	Shoot DW	2.1	2.5	MT
Wheatgrass, standard crested	<i>Agropyron sibiricum</i> (Willd.) Beauvois	Shoot DW	3.5	4.0	MT
Wheatgrass, fairway crested	<i>A. cristatum</i> (L.) Gaertn.	Shoot DW	7.5	6.9	T
Wheatgrass, intermediate	<i>A. intermedium</i> (Host) Beauvois	Shoot DW	—	—	MT*
Wheatgrass, slender	<i>A. trachycaulum</i> (Link) Malte	Shoot DW	—	—	MT
Wheatgrass, tall	<i>A. elongatum</i> (Hort) Beauvois	Shoot DW	7.5	4.2	T
Wheatgrass, western	<i>A. smithii</i> Rydb.	Shoot DW	—	—	MT*
Wildrye, Altai	<i>Elymus angustus</i> Trin.	Shoot DW	—	—	T
Wildrye, beardless	<i>E. triticoides</i> Buckl.	Shoot DW	2.7	6.0	MT
Wildrye, Canadian	<i>E. canadensis</i> L.	Shoot DW	—	—	MT*
Wildrye, Russian	<i>E. junceus</i> Fisch.	Shoot DW	—	—	T

Vegetable and fruit crops

Artichoke	<i>Cynara scolymus</i> L.	Bud yield	6.1	11.5	MT
Asparagus	<i>Asparagus officinalis</i> L.	Spear yield	4.1	2.0	T
Bean, common	<i>Phaseolus vulgaris</i> L.	Seed yield	1.0	19	S
Bean, lima	<i>P. lunatus</i> L.	Seed yield	—	—	MT*
Bean, mung	<i>Vigna radiata</i> (L.) R. Wilcz.	Seed yield	1.8	20.7	S
Cassava	<i>Manihot esculenta</i> Crantz	Tuber yield	—	—	MS
Beet, red ^k	<i>Beta vulgaris</i> L.	Storage root	4.0	9.0	MT
Broccoli	<i>Brassica oleracea</i> L. (Botrytis Group)	Head FW	1.3	15.8	MT
Brussels Sprouts	<i>B. oleracea</i> L. (Gemifera Group)	—	—	—	MS*
Cabbage	<i>B. oleracea</i> L. (Capitata Group)	Head FW	1.8	9.7	MS
Carrot	<i>Daucus carota</i> L.	Storage root	1.0	14	S
Cauliflower	<i>Brassica oleracea</i> L. (Botrytis Group)	—	1.5	14.4	MS*
Celery	<i>Apium graveolens</i> L. var <i>dulce</i> (Mill.) Pers.	Petiole FW	1.8	6.2	MT
Corn, sweet	<i>Zea mays</i> L.	Ear FW	1.7	12	MS
Cowpea	<i>Vigna unguiculata</i> (L.) Walp.	Seed yield	4.9	12	MT

(continued)

TABLE 13-1. Salt Tolerance of Herbaceous Crops^a (Continued)

Crop			Salt-Tolerance Parameters		
Common Name (1)	Botanical Name ^b (2)	Tolerance Based On: (3)	Threshold ^c (EC _e) (dS/m) (4)	Slope (% per dS/m) (5)	Rating ^d (6)
Cucumber	<i>Cucumis sativus</i> L.	Fruit yield	2.5	13	MS
Eggplant	<i>Solanum melongena</i> L. var <i>esculentum</i> Nees.	Fruit yield	1.1	6.9	MS
Fennel	<i>Foeniculum vulgare</i> Mill.	Bulb yield	1.4	16	S
Garlic	<i>Allium sativum</i> L.	Bulb yield	3.9	14.3	MS
Gram, black or Urd bean	<i>Vigna mungo</i> (L.) Hepper [syn. <i>Phaseolus mungo</i> L.]	Shoot DW	—	—	S
Kale	<i>Brassica oleracea</i> L. (Acephala Group)		—	—	MS*
Kohlrabi	<i>Brassica oleracea</i> L. (Gongylodes Group)		—	—	MS*
Lettuce	<i>Lactuca sativa</i> L.	Top FW	1.3	13	MS
Muskmelon	<i>Cucumis melo</i> L. (Reticulatus Group)	Fruit yield	1.0	8.4	MS
Okra	<i>Abelmoschus esculentus</i> (L.) Moench	Pod yield	—	—	MS
Onion (bulb)	<i>Allium cepa</i> L.	Bulb yield	1.2	16	S
Onion (seed)		Seed yield	1.0	8.0	MS
Parsnip	<i>Pastinaca sativa</i> L.		—	—	S*
Pea	<i>Pisum sativum</i> L.	Seed FW	3.4	10.6	MS
Pepper	<i>Capsicum annuum</i> L.	Fruit yield	1.5	14	MS
Pigeon pea	<i>Cajanus cajan</i> (L.) Huth [syn. <i>C. indicus</i> (K.) Spreng.]	Shoot DW	—	—	S
Potato	<i>Solanum tuberosum</i> L.	Tuber yield	1.7	12	MS
Pumpkin	<i>Cucurbita pepo</i> L. var <i>Pepo</i>		—	—	MS*
Purslane	<i>Portulaca oleracea</i> L.	Shoot FW	6.3	9.6	MT
Radish	<i>Raphanus sativus</i> L.	Storage root	1.2	13	MS
Spinach	<i>Spinacia oleracea</i> L.	Top FW	2.0	7.6	MS
Squash, scallop	<i>Cucurbita pepo</i> L. var <i>melopepo</i> (L.) Alef.	Fruit yield	3.2	16	MS
Squash, zucchini	<i>C. pepo</i> L. var <i>melopepo</i> (L.) Alef.	Fruit yield	4.9	10.5	MT

Strawberry	<i>Fragaria x Ananassa</i> Duch.	Fruit yield	1.0	33	S
Sweet potato	<i>Ipomoea batatas</i> (L.) Lam.	Fleshy root	1.5	11	MS
Swiss chard	<i>Beta vulgaris</i> L.	Top FW	7.0	5.7	T
Tepary bean	<i>Phaseolus acutifolius</i> Gray		—	—	MS*
Tomato	<i>Lycopersicon lycopersicum</i> (L.) Karst. ex Farw. [syn. <i>Lycopersicon esculentum</i> Mill.]	Fruit yield	2.5	9.9	MS
Tomato, cherry	<i>L. lycopersicum</i> var. <i>Cerasiforme</i> (Dunal) Alef.	Fruit yield	1.7	9.1	MS
Turnip	<i>Brassica rapa</i> L.	Storage root	0.9	9.0	MS
Turnip (greens)	(Rapifera Group)				
		Top FW	3.3	4.3	MT
Watermelon	<i>Citrullus lanatus</i> (Thunb.) Matsum. & Nakai	Fruit yield	—	—	MS*
Winged bean	<i>Psophocarpus tetragonolobus</i> L. DC	Shoot DW	—	—	MT

^aThese data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on climate, soil conditions, and cultural practices.

^bBotanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.

^cIn gypsiferous soils, plants will tolerate EC_e of about 2 dS/m higher than indicated.

^dRatings with an * are estimates.

^eLess tolerant during seedling stage; EC_e at this stage should not exceed 4 or 5 dS/m.

^fUnpublished U. S. Salinity Laboratory data

^hGrain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m.

ⁱBecause paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil-water while the plants are submerged. Less tolerant during seedling stage.

^jSesame cultivars Sesaco 7 and 8 may be more tolerant than indicated by the S rating.

^kSensitive during germination and emergence; EC_e should not exceed 3 dS/m.

^lData from one cultivar, Probred.

^mAverage of several varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.

ⁿAverage for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.

*Estimated.

DW, dry weight; FW, fresh weight; S, sensitive; MS, moderately sensitive; MT, moderately tolerant; T, tolerant.

Adapted from Maas and Grattan (1999).

range from 1 to 3 dS m⁻¹ higher than that of nongypsiferous soils having a similar soil water conductivity value at field capacity (Bernstein 1962). The extent of this dissolution depends on the exchangeable ion composition, cation exchange capacity, and solution composition. Therefore, plants grown on gypsiferous soils will tolerate EC_es approximately 2 dS m⁻¹ higher than those listed in Table 13-1. The last column provides a qualitative salt tolerance rating that is useful in categorizing crops in general terms. The limits of these categories are illustrated in Fig. 13-1. Some crops are listed with only a qualitative rating, because experimental data are inadequate to calculate the threshold and slope.

The salt tolerance parameters shown in Table 13-1 are given in terms of the relative, rather than absolute, yield response under salinity, and for that reason may be somewhat misleading for growers in selecting crops for maximum yield and profitability given specific saline field conditions. Comparison of the relative and absolute yields of alfalfa, a high-value, high-quality leguminous forage, and tall wheatgrass, a forage of moderate value and quality, provides a good illustration. The salt tolerance threshold and slope, expressed on a relative yield basis, for alfalfa are 2 dS m⁻¹ and 7.3%, respectively; the crop is rated as moderately salt-sensitive. Tall wheatgrass, conversely, is considerably more tolerant to salinity; threshold-slope values are 7.5 dS m⁻¹ and 4.2%, respectively (Table 13-1).

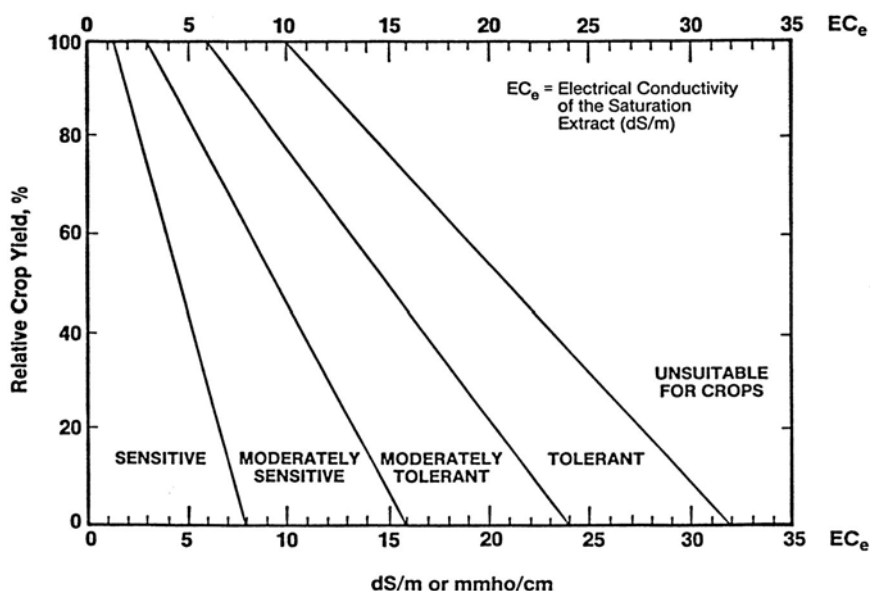


FIGURE 13-1. Divisions for classifying crop tolerance to salinity. From Maas and Hoffman (1977).

A year-long greenhouse sand culture experiment was conducted at the U.S. Salinity Laboratory in which both crops were irrigated with waters at two salinity levels: 15 and 25 dS m⁻¹ (Grattan et al. 2004a). In this system, irrigation water salinity (EC_i) is equivalent to that of the sand water (EC_{sw}) which, in turn, is approximately 2.2 times the EC of the saturated-soil extract (EC_e). The soil-water dynamics of the sand are similar to those found in field soils (Wang 2002). The salinity treatments were, therefore, estimated at 7.0 and 11.7 dS m⁻¹ expressed as EC_e. The threshold-slope model predicts that at the lower salinity (7 dS m⁻¹), the relative yield of tall wheatgrass would not be reduced at all, but that alfalfa yield would be reduced more than 40%. However, annual absolute biomass production for alfalfa irrigated with 15-dS m⁻¹ waters was 28 t ha⁻¹, whereas tall wheatgrass produced 20 t ha⁻¹ in the same treatment. As irrigation water salinity increased to 25 dS m⁻¹, the relative salt sensitivity of alfalfa became obvious inasmuch as absolute biomass was reduced by nearly 50% (15 t ha⁻¹). In contrast, biomass of tall wheatgrass was reduced only 15% in response to the higher salinity. It is likely that if salinity increased even further (e.g., to EC_i = 30 dS m⁻¹) the survivability of alfalfa would be in question, although tall wheatgrass would, in all probability, maintain reasonable biomass production. Therefore, both salt tolerance and absolute biomass production must be considered in crop selection. Clearly the grower must have a priori knowledge of the overall crop production potential in order to make an appropriate crop selection for anticipated saline field conditions.

Woody crops

The salt tolerance of trees, vines, and other woody crops is complicated because of additional detrimental effects caused by specific-ion toxicities. Many perennial woody species are susceptible to foliar injury caused by the toxic accumulation of Cl⁻ and/or Na⁺ in the leaves. Because different cultivars and rootstocks absorb and transport Cl⁻ and Na⁺ at different rates, considerable variation in tolerance may occur within an individual species. Tolerances to these specific ions are discussed in the following.

In the absence of specific-ion effects, the salt tolerance of woody crops, like that of herbaceous crops, can be expressed as a function of the concentration of total soluble salts or osmotic potential of the soil solution. One could expect this response to be obtained for those cultivars and rootstocks that restrict the uptake of Cl⁻ and Na⁺. The salt tolerance data given in Table 13-2 for woody crops are believed to be reasonably accurate in the absence of specific-ion toxicities. Because of the cost and time required to obtain fruit yields for extended periods of time (i.e., multiple years), particularly for alternate-bearing trees, tolerances of woody crops have been determined for vegetative growth only. In contrast to other

TABLE 13-2. Salt Tolerance of Woody Crops^a

Crop			Salt-Tolerance Parameters		
Common Name (1)	Botanical Name ^b (2)	Tolerance Based On: (3)	Threshold ^c (EC _e) (dS/m) (4)	Slope (% per dS/m) (5)	Rating ^d (6)
Almond	<i>Prunus dulcis</i> (Mill.) D.A. Webb	Shoot growth	1.5	19	S
Apple	<i>Malus sylvestris</i> Mill.		—	—	S
Apricot	<i>Prunus armeniaca</i> L.	Shoot growth	1.6	24	S
Avocado	<i>Persea americana</i> Mill.	Shoot growth	—	—	S
Banana	<i>Musa acuminata</i> Colla	Fruit yield	—	—	S
Blackberry	<i>Rubus macropetalus</i> Doug. ex Hook	Fruit yield	1.5	22	S
Boysenberry	<i>Rubus ursinus</i> Cham. and Schlechtend	Fruit yield	1.5	22	S
Castorbean	<i>Ricinus communis</i> L.		—	—	MS [*]
Cherimoya	<i>Annona cherimola</i> Mill.	Foliar injury	—	—	S
Cherry, sweet	<i>Prunus avium</i> L.	Foliar injury	—	—	S [*]
Cherry, sand	<i>Prunus besseyi</i> L., H. Baley	Foliar injury, stem growth	—	—	S [*]
Coconut	<i>Cocos nucifera</i> L.		—	—	MT [*]
Currant	<i>Ribes</i> sp. L.	Foliar injury, stem growth	—	—	S [*]
Date palm	<i>Phoenix dactylifera</i> L.	Fruit yield	4.0	3.6	T
Fig	<i>Ficus carica</i> L.	Plant DW	—	—	MT [*]
Gooseberry	<i>Ribes</i> sp. L.		—	—	S [*]
Grape	<i>Vitis vinifera</i> L.	Shoot growth	1.5	9.6	MS
Grapefruit	<i>Citrus x paradisi</i> Macfady	Fruit yield	1.2	13.5	S
Guava	<i>Psidium guajava</i> L.	Shoot and root growth	4.7	9.8	MT
Guayule	<i>Parthenium argentatum</i> A. Gray	Shoot DW	8.7	11.6	T
		Rubber yield	7.8	10.8	T
Jambolan plum	<i>Syzygium cumini</i> L.	Shoot growth	—	—	MT
Joboba	<i>Simmondsia chinensis</i> (Link) C. K. Schneid	Shoot growth	—	—	T
Jujube, Indian	<i>Ziziphus mauritiana</i> Lam.	Fruit yield	—	—	MT
Lemon	<i>Citrus limon</i> (L.) Burm. f.	Fruit yield	1.5	12.8	S
Lime	<i>Citrus aurantiifolia</i> (Christm.) Swingle		—	—	S [*]
Loquat	<i>Eriobotrya japonica</i> (Thunb). Lindl.	Foliar injury	—	—	S [*]

Macadamia	<i>Macadamia integrifolia</i> Maiden & Betcher	Seedling growth	—	—	MS*
Mandarin orange; tangerine	<i>Citrus reticulata</i> Blanco	Shoot growth	—	—	S*
Mango	<i>Mangifera indica</i> L.	Foliar injury	—	—	S
Natal plum	<i>Carissa grandiflora</i> (E.H. Mey.) A. DC.	Shoot growth	—	—	T
Olive	<i>Olea europaea</i> L.	Seedling growth, Fruit yield	—	—	MT
Orange	<i>Citrus sinensis</i> (L.) Osbeck	Fruit yield	1.3	13.1	S
Papaya	<i>Carica papaya</i> L.	Seedling growth, foliar injury	—	—	MS
Passion fruit	<i>Passiflora edulis</i> Sims		—	—	S*
Peach	<i>Prunus persica</i> (L.) Batsch	Shoot growth, Fruit yield	1.7	21	S
Pear	<i>Pyrus communis</i> L.		—	—	S*
Pecan	<i>Carya illinoensis</i> (Wangenh.) C. Koch	Nut yield, trunk growth	—	—	MS
Persimmon	<i>Diospyros virginiana</i> L.		—	—	S*
Pineapple	<i>Ananas comosus</i> (L.) Merrill	Shoot DW	—	—	MT
Pistachio	<i>Pistacia vera</i> L.	Shoot growth	—	—	MS
Plum; Prune	<i>Prunus domestica</i> L.	Fruit yield	2.6	31	MS
Pomegranate	<i>Punica granatum</i> L.	Shoot growth	—	—	MS
Popinac, white	<i>Leucaena leucocephala</i> (Lam.) de Wit [syn. <i>Leucaena glauca</i> Benth.]	Shoot DW	—	—	MS
Pummelo	<i>Citrus maxima</i> (Burm.)	Foliar injury	—	—	S*
Raspberry	<i>Rubus idaeus</i> L.	Fruit yield	—	—	S
Rose apple	<i>Syzygium jambos</i> (L.) Alston	Foliar injury	—	—	S*
Sapote, white	<i>Casimiroa edulis</i> Llave	Foliar injury	—	—	S*
Scarlet wisteria	<i>Sesbania grandiflora</i>	Shoot DW	—	—	MT
Tamarugo	<i>Prosopis tamarugo</i> Phil	Observation	—	—	T
Walnut	<i>Juglans</i> spp.	Foliar injury	—	—	S*

*These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on climate, soil conditions, and cultural practices. The data are applicable when rootstocks are used that do not accumulate Na⁺ or Cl⁻ rapidly or when these ions do not predominate in the soil.

^bBotanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.

^cIn gypsiferous soils, plants will tolerate EC_e about 2 dS/m higher than indicated.

^dRatings with an * are estimates.

*Estimated.

DW, dry weight; FW, fresh weight; S, sensitive; MS, moderately sensitive; MT, moderately tolerant; T, tolerant.

Adapted from Maas and Grattan (1999).

crop groups, most woody fruit and nut crops tend to be salt-sensitive, even in the absence of specific-ion effects. Only the date palm is rated as relatively salt-tolerant. Olives, pistachios, and a few others are believed to be tolerant to moderately high salinity, at least during the first few years of growth. As time under exposure to salts increased, however, tolerance may decline due to progressive toxic levels of salts accumulated in leaves or woody tissues. The long-term effects of olives grown under field conditions provide a striking example. Two years after planting and imposition of salt stress, the olive cultivar Arbequina was rated in 1999 as salt-tolerant with a threshold (EC_e) of 6.7 dS m^{-1} . In 2000, the threshold decreased to 4.7 dS m^{-1} . By 2001, Arbequina was rated as moderately salt-sensitive as the threshold declined to 3.0 dS m^{-1} (Aragüés et al. 2005). However, this decline in salt tolerance over the years was not observed in plums. The more salt-sensitive Santa Rosa plum (*Prunus salicina* Lindl) on Marianna 2624 rootstock (*P. cerasifera* Ehrh. $\times$ *P. munsoniana* Wight and Hedr.) showed little change in tolerance due to age. At the end of a 6-year field trial, the salt tolerance parameters (i.e., threshold = 2.6 dS m^{-1} ; slope = 31%) based on fruit yield determined after the first 3 years of the trial (1984–1985) were not significantly different than those obtained for 1987–1989 (Catlin et al. 1993).

Quality of salt-stressed agronomic and horticultural crops

While crop salt tolerance is based solely on yield, salinity adversely affects the quality of some crops. By decreasing the size and/or quality of fruits, tubers, or other edible organs, salinity reduces the market value of many vegetables, such as carrots, celery, cucumbers, peppers, potatoes, head cabbage and lettuce, artichoke, and yams (Bernstein et al. 1951; Bernstein 1964; Francois and West 1982; Francois 1991, 1995). Rye grown on saline soils produces grain with poorer bread-baking quality (Francois et al. 1989). Salinity appears to have only limited effect on the quality of citrus fruit (Maas 1993).

Not all the effects of salinity on crop quality are negative, however (Grieve 2010). Salinity often confers beneficial effects on crops, which may translate into economic advantages (Pasternak and De Malach 1994). Salinity can increase yields in crops that show a strong competition for photosynthates between vegetative and reproductive structures. In certain crops, salt stress can slow growth of the vegetative parts, allowing the excess photosynthates to flow to the generative organs. Cotton is a good example of such a crop. Saline water ($EC_e = 4.4 \text{ dS/m}$) irrigation resulted in 15% increases in fruit dry matter (g/plant) and number of bolls on fruiting branches as well as a 20% increase in boll number per plant (Pasternak et al. 1979). Although final internode number was reduced by 11%, reduction in total dry matter yield and plant height was not significant.

In addition to the conservation of high-quality waters, the controlled use of degraded waters offers a second benefit by providing a unique opportunity for the production of value-added crops with health-promoting constituents (Grieve 2010). Many plants adapt to salt stress by enhanced biosynthesis of secondary metabolites, such as soluble solids, sugars, organic acids, proteins, and amino acids (Ashraf and Harris 2004), which may act as osmolytes or osmoregulators to maintain plant turgor under salt stress. The presence of these metabolites often greatly increases the nutritive quality and marketability of fruits and vegetables (Mizrahi and Pasternak 1985). Beneficial effects include increased sugar concentration of carrots (Bernstein and Ayers 1953) and asparagus (Francois 1987), increased total soluble solids in tomatoes (Adams and Ho 1989; Krauss et al. 2006; Campos et al. 2006), muskmelon (Shannon and Francois 1978; Botia et al. 2005; Colla et al. 2006), cucumber (Chartzoulakis 1992; Trajkova et al. 2006), mandarin orange (Garcia-Sanchez et al. 2006), and improved grain quality and protein content of durum (Francois et al. 1986) and bread wheat (Rhoades et al. 1988). Salt-stress may increase firmness and improve postharvest handling characteristics in eggplants (Sifola et al. 1995), strawberries (Sarooshi and Cresswell 1994), tomatoes (Krauss et al. 2006), and melons (Navarro et al. 1999). Onion bulb pungency may be reduced by salt-stress, although the content of flavor precursors often increases (Chang and Randle 2005). Salinity may also cause oxidative stress and induce production of reactive oxygen species, which are damaging to all classes of biomolecules. The primary defensive plant response to oxidative stress is the biosynthesis of antioxidants (Bartosz 1997). As a result, salt-stressed plants often contain enhanced concentrations of antioxidants, such as flavonoids, ascorbate, tocopherols, carotenoids, and lycopene. With proper management practices, it is likely that economic losses associated with yield reductions due to salinity may be offset by production of high-quality food crops that can be marketed at a premium to meet the changing demands of the market and health-conscious consumers (Cuarto and Fernández-Muñoz 1999; De Pascale et al. 2001).

Ornamental and landscape species

Research on the salt tolerance of floriculture species continues to be largely devoted to providing information that would help commercial growers maintain crop productivity, quality, and profitability if recycled waters are used for irrigation. Quality standards for landscape use are far less stringent than those required by the floriculture industry. For example, a major quality determinant for important cut flowers is stem length, a growth parameter that is generally reduced when the plant is challenged by salinity. In their drive for high-quality products suitable for

premium markets, commercial growers would likely use the highest-quality water available to maximize inflorescence length, flower diameter, and plant height. However, a flowering stalk of stock (*Matthiola incana*), a moderately salt-sensitive crop, would still be aesthetically acceptable for landscape purposes if, compared to a premium-grade stalk, the flowering stem was 5 cm shorter and the inflorescence contained one or two fewer florets. Minimal reduction in growth and flowering capacity should be permissible, provided that the overall health of the plant is not compromised, the stems are robust, the colors of the leaves and flowers remain true, and no visible leaf or flower damage due to salt stress is evident. For landscape purposes, stock is rated as very salt-tolerant.

Applying salt-tolerance criteria derived from the ecophysiological literature to landscape plants sometimes results in completely misleading tolerance ratings. The performance of statice (*Limonium* spp.) under saline conditions provides a good example. In HALOPH, a database of salt-tolerant plants of the world, Aronson (1989) lists more than 50 species of *Limonium*. The commercially important species, *L. perezii* and *L. sinuatum*, are listed among those that will complete their life cycles in waters more salty than seawater (e.g., $EC > 50$ dS/m). That these species grow to maturity under highly saline conditions is clearly a halophytic characteristic. Although one would not expect either species to produce a high-quality crop under irrigation with hypersaline waters, the question arose: Could flowers suitable for the commercial market or for landscape purposes be produced at lower salinities, for example, in the range of 20 to 30 dS m^{-1} ? To answer this question, both statice species were grown under irrigation with waters ranging from 2 to 30 dS m^{-1} (Grieve et al. 2005; Carter et al. 2005). These trials confirmed that both species were halophytic; both flowered and set seed in all treatments. However, neither species possessed a high degree of salt tolerance as understood by horticulturists and agronomists whose research focuses on crop yield and quality. Growth response of statice more closely resembled that of glycophytic plants. Height of the flowering stalks decreased consistently as salinity increased. Those plants receiving the 30-dS m^{-1} treatment were only one-quarter as tall as those irrigated with nonsaline waters. The salt tolerance of both species, rated for commercial production on the basis of stem length, is correctly rated as low (Farnham et al. 1985). Reduction in stem length should not necessarily be the limiting factor in species selection for landscape plants, however. Even under severe salt stress, both 'American Beauty' and 'Blue Seas' produced acceptable, healthy plants with attractive foliage and colorful inflorescences on sturdy, albeit short, stems. For landscape purposes, the species fall in the "very tolerant" category.

Many examples are available illustrating that the effects of salinity on landscape plants are not always adverse. Salt-related stress can benefi-

cially affect quality and disease resistance of plants. If plant aesthetics are not compromised, salt-stressed landscape plants will be slower growing, requiring less trimming and maintenance. In some instances, the uptake and accumulation of salinizing ions stimulates growth. Cabrera (2000) and Cabrera and Perdomo (2003) observed a positive correlation between relatively high leaf-Cl concentrations (0.45%) and dry weight for container-grown rose ('Bridal Pink' on *Rosa manetti* rootstock). Yield and quality were unaffected. Salinity imposed early in the life cycle of some cut-flower species tends to limit vegetative growth, with favorable results. Salinity-induced reduction of stem length may be beneficial in species such as chrysanthemum, where tall, rangy cultivars are treated with growth regulators to keep the plants compact and short. While plant height is often reduced by moderate salinity, the length of time to maturity and the size of developing floral buds generally remain unaffected by stress (Lieth and Burger 1989).

Salt tolerance ratings of selected landscape species (Table 13-3) are based on aesthetic value and survivability. In some cases, two contrasting ratings are given. Differences may be due to variety, climatic, or nutritional conditions under which the trials were conducted. In addition, some of the ratings are derived from data collected from closely related varieties of horticultural or agronomic value. There are no data, for example, on the salt tolerance of ornamental brassicas, such as kale and cabbage, but it would be reasonable to assume that their salt tolerance would not differ very sharply from that of the same leafy vegetable crop grown under field conditions in agricultural settings.

Excellent resources for additional information regarding the salt tolerance of landscape plants are the *Salt Management Guide* (Tanji 2007) and *Abiotic Disorders of Landscape Plants: A Diagnostic Guide* (Costello et al. 2003).

Potential uses of halophytes

A promising approach for the practical use of heavily salinized soils and waters that are otherwise unsuitable for conventional agriculture is the use of highly salt-tolerant plant species, (halophytes). Many halophytes are valuable for economic reasons (human food, fodder, oil, fuel) or for ecological reasons, such as dune stabilization, erosion control, CO₂ sequestration, reclamation, and desalinization (Koyro 2003). True halophytes are defined as those plants that are able to survive and complete their life cycles in hypersaline environments and whose maximum growth occurs at a soil water salinity of ~20 dS/m (Salisbury 1995). Halophytes have developed a number of morphological adaptations and physiological mechanisms to avoid and resist salt stress: salt hairs and salt glands, waxy cuticles, selective ion uptake, salt exclusion from different

TABLE 13-3. Salt Tolerance of Selected Landscape Plants

Botanical Name (1)	Common Name (2)	Salt Tolerance ^a (3)
<i>Agapanthus orientalis</i>	Lily of the Nile	sensitive
<i>Ageratum houstonianum</i>	Ageratum	moderately sensitive
<i>Alstroemeria hybrids</i>	Inca lily, Peruvian lily	very sensitive
<i>Amaranthus hypochondriacus</i>	Pygmy Torch	tolerant
<i>Amaranthus tricolor</i>	Love-Lies-Bleeding	tolerant
<i>Anthurium andreanum</i>	Anthurium	very sensitive
<i>Antirrhinum majus</i>	Snapdragon	tolerant
<i>Artemesia stelleran</i>	Dusty Miller	moderately sensitive
<i>Begonia bunchii</i>	Begonia	sensitive
<i>Begonia Rex-cultorum</i>	Rex Begonia	very sensitive
<i>Begonia ricinifolia</i>	Begonia	sensitive
<i>Bouvardia longiflora</i>	Bouvardia	moderately sensitive
<i>Brassica oleracea</i>	Ornamental Cabbage	sensitive
<i>Brassica oleracea</i>	Ornamental Kale	sensitive
<i>Calendula officinalis</i>	Pot Marigold	moderately tolerant
<i>Callistephus chinensis</i>	China Aster	moderately sensitive
<i>Calocephalus brownii</i>	Cushion Bush	moderately tolerant
<i>Camellia japonica</i>	Camellia	moderately sensitive
<i>Carathamus tinctorius</i>	Safflower	sensitive
<i>Catharanthus roseus</i>	Vinca	moderately tolerant
<i>Celosia argenta cristata</i>	Crested Coxcomb	sensitive
<i>Celosia argenta cristata</i>	Chief Celosia	moderately sensitive
<i>Cereus peruviana</i>	Apple Cactus	tolerant
<i>Chlorophytum comosum</i>	St. Bernard's Lily	moderately sensitive
<i>Chrysanthemum morifolium</i>	Mum	tolerant
<i>Clematis orientalis</i>	Clematis	moderately tolerant
<i>Coleus blumei</i>	Coleus	very tolerant
<i>Codiaeum punctatus</i>	Croton	tolerant
<i>Consolida ambigua</i>	Larkspur	moderately tolerant
<i>Cosmos bipinnatus</i>	Cosmos	sensitive
<i>Coreopsis grandiflora</i>	Coreopsis	very sensitive
<i>Crassula ovata</i>	Jade Plant	moderately sensitive
<i>Cyclamen persicum</i>	Cyclamen	moderately sensitive
<i>Cymbidium spp.</i>	Orchid	sensitive
<i>Dianthus barbatus</i>	Pinks	very sensitive
<i>Dianthus caryophyllus</i>	Carnation	moderately sensitive
<i>Dianthus chinensis</i>	Carnation	moderately tolerant
<i>Eschscholzia californica</i>	California Poppy	moderately tolerant
<i>Euphorbia pulcherrima</i>	Poinsettia 'Red Sails'	moderately tolerant
<i>Euphorbia pulcherrima</i>	Poinsettia 'Barbara Ecke'	sensitive
<i>Euryops pectinatus</i>	Golden Marguerite	very sensitive
<i>Eustoma grandiflorum</i>	Lisianthus	sensitive
		moderately sensitive

TABLE 13-3. Salt Tolerance of Selected Landscape Plants (*Continued*)

Botanical Name (1)	Common Name (2)	Salt Tolerance ^a (3)
<i>Felicia amelloides</i>	Felicia	sensitive
<i>Fuchsia hybrida</i>	Fuchsia	very sensitive
<i>Gardenia augusta</i>	Gardenia	sensitive
<i>Gazania aurantiacum</i>	Gazania	moderately tolerant
<i>Gerbera jamesonii</i>	Gerbera Daisy	moderately sensitive
<i>Gazania spp.</i>	Treasure Flower	very tolerant
<i>Gladiolus spp.</i>	Gladiola	sensitive
<i>Gomphrena globosa</i>	Globe Amaranth	moderately sensitive
<i>Gypsophila paniculata</i>	Baby's Breath	moderately tolerant
<i>Helianthus annuus</i>	Sunflower	moderately tolerant
<i>Helianthus debilis</i>	Cucumber Leaf	very tolerant
<i>Hibiscus rosa-sinensis</i>	Hibiscus	sensitive
<i>Hippeastrum hybridum</i>	Amaryllis	very sensitive
<i>Hymenocallis keyensis</i>	Spiderlily	moderately tolerant
<i>Impatiens x hawkeri</i>	Impatiens	sensitive
<i>Kalanchoe spp.</i>	Kalanchoe	moderately tolerant
<i>Kochia childsii</i>	Kochia	tolerant
<i>Lathyrus japonica</i>	Sweet Pea	moderately tolerant
<i>Lilium spp.</i>	Asiatic Hybrid Lily	sensitive
<i>Lilium spp.</i>	Oriental Hybrid Lily	sensitive
<i>Limonium spp.</i>	Japanese Limonium	very tolerant
<i>Limonium latifolium</i>	Sea Lavender	very tolerant
<i>Limonium perezii</i>	Statice	Sensitive; very tolerant
<i>Limonium sinuatum</i>	Statice	Sensitive; very tolerant
<i>Lobularia maritima</i>	Sweet Alyssum	moderately tolerant
<i>Matthiola incana</i>	Stock	very tolerant
<i>Narcissus tazetta</i>	Paperwhite Narcissus	sensitive
<i>Oenothera speciosa</i>	Mexican Evening Primrose	moderately tolerant
<i>Ophiopogon jaburan</i>	Giant Turf Lily	moderately sensitive
<i>Ornithogalum arabicum</i>	Arabian Star Flower	very sensitive
<i>Pelargonium x hortorum</i>	Geranium	sensitive
<i>Pelargonium domesticum</i>	Geranium	tolerant
<i>Pelargonium peltatum</i>	Ivy Geranium	moderately tolerant
<i>Petunia hybrida</i>	Petunia	tolerant
<i>Portulaca grandiflora</i>	Moss Rose	very tolerant
<i>Phalaenopsis hybrid</i>	Orchid	very sensitive
<i>Protea obtusifolia</i>	Protea	moderately tolerant
<i>Rhododendron hybrids</i>	Azalea	moderately sensitive
<i>Rhododendron obtusum</i>	Azalea	sensitive
<i>Rosa x hybrida</i>	Rose	sensitive
<i>Stapelia gigantea</i>	Starfish Flower	moderately tolerant

(continued)

TABLE 13-3. Salt Tolerance of Selected Landscape Plants (*Continued*)

Botanical Name (1)	Common Name (2)	Salt Tolerance ^a (3)
<i>Strelitzia reginae</i>	Bird of Paradise	very sensitive
<i>Tagetes erecta</i>	Marigold	moderately tolerant
<i>Tagetes patula</i>	Marigold	moderately tolerant
<i>Trachelium caeruleum</i>	Blue Throatwort	sensitive
<i>Tropaeolum majus</i>	Nasturtium	moderately sensitive
<i>Vinca major</i>	Periwinkle	moderately tolerant
<i>Vinca minor</i>	Myrtle	sensitive
<i>Viola x wittrockiana</i>	Pansy	sensitive
<i>Zinnia elegans</i>	Zinnia	moderately sensitive

^aCriteria for assigning salt tolerance: not more than 50% reduction in growth, no visually observable foliar burn, and maximum permissible ECe (dS m⁻¹) as follows:

- <2 very sensitive
- 2–3 sensitive
- 3–4 moderately sensitive
- 4–5 moderately tolerant
- 5–6 tolerant
- >6 very tolerant

Adapted from Grieve et al. (2007) and Tanji (2007).

plant organs (root, stem, leaf or fruit), salt sequestration in vacuoles or in senescent leaves, succulence, dilution of plant salt concentration by increased growth, osmotic adjustment, compatible osmotic solutes, root excretion of salts, and root molecular sieves (Ungar 1998).

Halophytes may also be of value in water treatment. Improvement of water quality through the use of natural or constructed wetlands is a relatively new concept for treating effluents from agricultural operations, such as dairies, livestock feedlots (Ibekwe et al. 2003; Ibekwe et al. 2007; Ray and Inouye 2007), and nurseries (Arnold et al. 2003). Wastewaters from agricultural operations are generally brackish and typically contain high levels of nutrients and other pollutants. Vegetation plays a significant role in wastewater purification by reducing nitrogen and the biochemical oxygen demand and removal of suspended solids (Gersberg et al. 1986). Certain aquatic plant species possess unique anatomical and morphological features that together with their pollutant uptake capacity and survivability, make them of prime importance in wetlands ecosystems. Wetland species improve water quality by direct uptake of nutrients and also by reducing water velocity, which allows suspended particles to settle (Ray and Inouye 2007). Ecologically valuable species for these purposes include bulrush (*Scirpus validus*), common tule (*S. acutus*), rush (*Juncus balticus*), spike rush (*Eleocharis palustris*),

common reed (*Phragmites communis*), cattail (*Typha latifolia*), and carex (*Carex nebrascensis*).

Additional information concerning ecologically important species may be found in HALOPH (Aronson 1989). This compilation lists halophytic crops by plant family and gives maximum reported salinity tolerance, geographical distribution, and potential economic uses for many species. Another valuable resource is *Cash Crop Halophytes* (Lieth and Mochtchenko 2003), which addresses topics, such as ecophysiological research on salt tolerance of plants, halophyte utilization for reclamation of soils, and sustainable systems under irrigation with seawater. A CD-ROM accompanies the text and gives taxonomic classification and highest reported salinity tolerance for more than 2,000 species.

SALINITY AND NUTRITIONAL IMBALANCE

Salinity can induce elemental nutrient deficiencies or imbalances in plants depending on the ionic composition of the external solution. These specific effects vary among species and even among varieties of a given crop. The optimal concentration range for a particular nutrient element in the soil solution depends on many factors, including salt concentration and composition (Grattan and Grieve 1994). This is not surprising since salinity affects nutrient ion activities and produces extreme ion ratios (e.g., $\text{Na}^+/\text{Ca}^{2+}$, Na^+/K^+ , $\text{Cl}^-/\text{NO}_3^-$) in the soil solution. Nutrient imbalances in the plant may result from the effect of salinity on (1) nutrient availability, (2) the uptake and/or distribution of a nutrient within the plant, and/or (3) increasing the internal plant requirement for a nutrient element resulting from physiological inactivation (Grattan and Grieve 1999).

A substantial body of information in the literature indicates that nutrient element acquisition by crops is reduced in saline environments, depending, of course, on the nutrient element in question and the composition of the salinizing solution. The activity of a nutrient element in the soil solution decreases as salinity increases, unless the nutrient in question is part of the salinizing salts (e.g., Ca^{2+} , Mg^{2+} , or SO_4^{2-}). For example, phosphate (P) availability is reduced in saline soils not only because the ionic-strength effect reduces the activity of phosphate, but also because its concentration is controlled by sorption processes and by the precipitation of Ca-P minerals. Therefore, P concentrations in many full-grown agronomic crops decrease as salinity increases (Sharpley et al. 1992). Soil salinity can affect nutrient acquisition by severely reducing root growth. Reductions of 40% to 50% have been reported in root weight and lengths of citrus and tomato (Zekri and Parsons 1990; Snapp and Shennan 1992).

Other evidence indicates that salinity may cause some physiological inactivation of P, thereby increasing the plant's internal requirement for this element (Awad et al. 1990). These investigators found that when NaCl concentrations were increased from 10 to 100 mM, P concentration in the youngest mature tomato leaf necessary to achieve 50% yield nearly doubled. Moreover, at any given leaf P concentration, foliar symptoms of P deficiency increased with increased NaCl salinity. It would not be surprising to find similar relationships involving other crops or even other nutrients.

Nutrient uptake and accumulation by plants is often reduced under saline conditions as a result of competitive processes between the nutrient and a major salt species. Although plants selectively absorb K^+ over Na^+ , Na^+ -induced K deficiencies can develop on crops under salinity stress by Na salts (Janzen and Chang 1987). On the other hand, Cl^- salts can reduce NO_3^- uptake and accumulation in crops even though this effect may not be growth-limiting (Munns and Termaat 1986).

Even under nonsaline conditions, significant economic losses of horticultural crops have been linked to inadequate calcium (Ca^{2+}) nutrition (Shear 1975). Many factors can influence the amount of plant-available Ca. These include the total supply of Ca^{2+} , the nature of the counter-ions, the pH of the substrate, and the ratio of Ca^{2+} to other cations in the irrigation water (Grattan and Grieve 1999). Calcium-related disorders may even occur in plants grown on substrates where the Ca^{2+} concentration appears to be adequate (Pearson 1959; Bernstein 1975). Deficiency symptoms are generally caused by differences in Ca^{2+} partitioning to the growing regions of the plant. All plant parts—leaves, stems, flowers, fruits—actively compete for the pool of available Ca^{2+} and each part influences Ca^{2+} movement independently. Organs that are most actively transpiring are those most apt to have the highest Ca^{2+} concentrations. In horticultural plants whose marketable product consists primarily of large heads enveloped by outer ("wrapper") leaves [e.g., cabbage, lettuce, escarole, or endive], excessive transpiration by the outer leaves diverts Ca^{2+} from the rapidly growing meristematic tissue (Bangerth 1979). Calcium deficiency appears as physiological disorders of the younger tissues: internal browning of cabbage and lettuce, blackheart of celery. Calcium deficiency disorders may also occur in reproductive tissues and may reduce market quality: blossom-end rot of tomatoes, melons, and peppers; "soft-nose" of mangoes and avocados; and cracking and "bitter pit" of apples. Artichokes grown under arid but nonsaline conditions also exhibits Ca-deficiency injury as necrosis of inner bracts. The incidence of the disorder increased when salt-stress was imposed (Francois 1995).

Any hazard to horticultural crops that are susceptible to Ca-related disorders in the absence of salinity becomes even greater under saline conditions. As the salt concentration in the rootzone increases, the plant's

requirement for Ca also increases (Bernstein 1975). At the same time, Ca uptake from the substrate may be depressed because of ion interactions, precipitation, and increases in ionic strength (Grattan and Grieve 1999). Significant reduction in market quality and associated economic losses occur when these susceptible crops are also challenged by salinity.

Sodium-induced Ca^{2+} deficiencies have been observed by many researchers when the $\text{Na}^+/\text{Ca}^{2+}$ ratio in the solution, at a given salinity level, increases above a threshold level. This is particularly true for many crops in the grass family (e.g., corn, sorghum, rice, wheat, and barley) and striking differences have been observed among species and cultivars. Calcium deficiency may be related, at least in part, to the effect of Na^+ on Ca^{2+} distribution within the plant. Some researchers found that Na^+ inhibits the radial movement of Ca^{2+} from the root epidermis to the root xylem vessels (Lynch and Läuchli 1985), while others found that Ca^{2+} transport to meristematic regions and developing leaves was inhibited (Maas and Grieve 1987; Grieve and Maas 1988). Salinity-induced Ca^{2+} deficiency has also been observed on crops from different families, such as blossom-end rot in tomatoes and bell peppers and black heart in celery (Geraldson 1957).

CROP RESPONSE TO SPECIFIC IONS AND ELEMENTS

In addition to osmotic effects that reduce plant biomass and yields and salinity's effect on mineral nutrition, specific ions (i.e., Na, Cl, and B) can cause additional injury to the crops, causing further crop damage. These specific ions will be discussed separately.

Sodium

Sodium is not considered an essential element for most crop plants, but it does beneficially affect growth of some plants at concentrations below the salt-tolerance threshold. At concentrations above the threshold, Na^+ can have both direct and indirect detrimental effects on plants. Direct effects are caused by the accumulation of toxic levels of Na^+ and are generally limited to woody species. The ability of a plant to tolerate excessive amounts of Na^+ varies widely among species and rootstocks. Na^+ injury on avocados, citrus, and stone fruit is rather widespread and can occur at Na^+ concentrations as low as 5 mol m^{-3} in soil water. The symptoms may not appear immediately after exposure to saline water, however. Initially, Na^+ is retained in the roots and lower trunk, but after 3 or 4 years the conversion of sapwood to heartwood apparently releases the accumulated Na^+ , which is transported to the leaves and causes leaf burn (Bernstein et al. 1956).

Indirect effects include both nutritional imbalance and impairment of soil physical conditions. The nutritional effects of Na^+ are not simply related to the exchangeable Na^+ percentage of soils but depend on the concentrations of Na^+ , Ca^{2+} , and Mg^{2+} in the soil solution. In sodic, non-saline soils, total soluble salt concentrations are low and, consequently, Ca^{2+} and/or Mg^{2+} concentrations are often nutritionally inadequate. These deficiencies, rather than Na^+ toxicity per se, are usually the primary cause of poor plant growth among nonwoody species and, in many cases, woody species as well. Furthermore, since Na^+ uptake by plants is strongly regulated by Ca^{2+} in the soil solution, the presence of sufficient Ca^{2+} is essential to prevent the accumulation of toxic levels of Na^+ . This is particularly important with Na^+ -sensitive woody crops. As a general guide, Ca^{2+} and Mg^{2+} concentrations in the soil solution above 1 mol m^{-3} each are nutritionally adequate in nonsaline, sodic soils (Carter et al. 1979; Hanson 1983).

As the total salt concentration increases into the saline-sodic range, Ca^{2+} concentrations become adequate for most plants and osmotic effects begin to predominate. However, some species are susceptible to salinity-induced Ca^{2+} deficiencies as previously indicated. Therefore, for most crops species, rather than having tolerance limits for Na^+ per se, it would be more valuable to list a favorable Na/Ca ratio or sodium adsorption ratio (SAR), an approach used by Ayers and Westcot (1985).

Sodic soil conditions affect almost all crops because of the deterioration of soil physical conditions. Dispersion of soil aggregates in sodic soils decreases soil permeability to water and air, thereby reducing plant growth. Poorly structured soils also result in prolonged saturated environments, encouraging root disease. Therefore, yield reductions in crops that are not specifically sensitive to Na^+ generally reflect the combined effects of nutritional problems and all problems associated with impaired soil physical conditions.

Chloride

Chlorine is an essential micronutrient for plants but, unlike most micronutrients, it is relatively nontoxic when supplied at low concentrations sufficient only to meet plant requirements (Maas 1986). In fact, most nonwoody crops are not specifically sensitive to Cl^- even at higher concentrations. One exception to this generalization involves certain cultivars of soybeans that tend to accumulate excessive and toxic amounts of Cl^- (Abel and McKenzie 1964; Parker et al. 1983). Tolerant cultivars restrict Cl^- transport to the shoots. Many woody species are also susceptible to Cl^- toxicity, which varies among varieties and rootstocks within species. As in soybeans, these differences usually reflect the plant's ability to prevent or retard Cl^- translocation to the shoots or scions. Cooper (1951, 1961) found that the salt tolerance of avocados, grapefruits, and oranges is

closely related to the Cl^- accumulation properties of the rootstocks. Similar effects of rootstocks on salt accumulation and tolerance have been reported for stonefruit (Bernstein et al. 1956) and nut trees (Ferguson et al. 2002). Large differences in the salt tolerance of grape varieties have been linked with the Cl^- -accumulating characteristics of different rootstocks (Ehlig 1960; Sauer 1968; Bernstein et al. 1969; Groot Obbink and Alexander 1973). By selecting rootstocks that exclude Cl^- from the scions, this problem can be avoided.

Table 13-4 lists the maximum Cl^- concentrations permissible in the soil water that do not cause leaf injury in selected fruitcrop cultivars and rootstocks. In some cases, however, the osmotic threshold may be exceeded so that yield is decreased without obvious injury. The list is by no means complete, and most popular rootstocks are not listed because quantitative data are not available.

The major detrimental effect of Cl^- results from its contribution to the overall osmotic stress. No comprehensive testing has been done to specifically determine crop tolerances to Cl^- salinity but, since most of the salt-tolerance data were obtained in field plots salinized with Cl salts of Na^+ and Ca^{2+} , the data can be converted to express tolerances in terms of Cl^- concentration. If Cl^- is the predominant anion in the soil solution, then Cl^- concentration $[\text{Cl}^-]$, expressed in meq/L (mmol/L) is approximately 10 times the EC expressed in dS/m (USSL 1954). Therefore, multiplying the threshold values given in Tables 13-1 and 13-2 by 10 gives the maximum allowable Cl^- concentration in mol m^{-3} in the saturated-soil extract without a loss in yield. Dividing the slope by 10 estimates the percent yield-potential decrease expected per each 1 mol m^{-3} increase in Cl^- concentration above the threshold.

Boron

Boron (B) is an essential micronutrient for plants. The optimum concentration range of plant-available B, however, is very narrow for most crops. Various criteria have been proposed to define levels that are necessary for adequate B nutrition and yet low enough to avoid B toxicity symptoms, plant injury, and subsequent yield reduction (Ayers and Westcot 1985; Gupta et al. 1985; Keren and Bingham 1985). Boron deficiency is more widespread than B toxicity, particularly in humid climates, whereas excess B toxicity tends to be more of a concern in arid environments. Like salt tolerance, B tolerance fluctuates with climate, soil conditions, and plant variety.

Much of the existing B tolerance data were obtained from experiments conducted from 1930 through 1934 by Eaton (1944). These data provided threshold tolerance limits for more than 40 different crops. While very useful, Eaton's experimental data cannot be fitted to any reliable

TABLE 13-4. Chloride Tolerance Limits of Some Fruit-Crop Rootstocks and Cultivars

Crop (1)	Rootstock or Cultivar (2)	Maximum Permissible Cl ⁻ in Soil Water without Leaf Injury ^a (mol m ⁻³) (3)
Rootstocks		
Avocado (<i>Persea americana</i>)	West Indian	15
	Guatemalan	12
	Mexican	10
Citrus (<i>Citrus</i> sp.)	Sunki mandarin, grapefruit	50
	Cleopatra mandarin, Rangpur lime	50
	Sampson tangelo, rough lemon	30
	Sour orange, Ponkan mandarin	30
	Citrumelo 4475, trifoliolate orange	20
	Cuban shaddock, Calamondin	20
	Sweet orange, Savage citrange	20
	Rusk citrange, Troyer citrange	20
Grape (<i>Vitis</i> sp.)	Salt Creek, 1613-3	80
	Dog Ridge	60
Stone fruit (<i>Prunus</i> sp.)	Marianna	50
	Lovell, Shalil	20
	Yunnan	15
Cultivars		
Berries ^b (<i>Rubus</i> sp.)	Boysenberry	20
	Olallie blackberry	20
	Indian Summer raspberry	10
Grape (<i>Vitis</i> sp.)	Thompson seedless, Perlette	40
	Cardinal, Black Rose	20
Strawberry (<i>Fragaria</i> sp.)	Lassen	15
	Shasta	10

^aFor some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction.

^bData available for one variety of each species only

Adapted from Maas and Grattan (1999).

growth-response function for most crops. Nevertheless, his results are the source of most of the threshold tolerance limits presented in Table 13-5. Plant response to excess B can be described by the two-piece linear response model (Bingham et al. 1985; Francois 1984, 1986, 1988, 1989, 1991, 1992). These data have provided threshold and slope parameters for a limited number of crops and are included in Table 13-5. With few exceptions, the B tolerance data are based on crop responses to different B levels in sand cultures. The thresholds indicate maximum permissible concentrations in the soil water that do not cause yield reductions. Some crops, however, may exhibit leaf injury at low to moderate concentrations without decreasing yield. For example, heavy leaf damage due to long-term B accumulation in grapes had no effect on the commercial fruit yield (Yermiyahu et al. 2006). Based on response to B, crops have been classified in six groups, ranging from very sensitive to very tolerant. Like salt tolerance, B tolerance varies with climate, soil conditions, and crop cultivars; therefore the data may not apply to all cultural conditions. Because different rootstocks of citrus and stone fruits absorb B at different rates, that tolerance will likely be improved by using rootstocks that restrict B uptake. A number of these rootstocks are listed in order of increasing B accumulation in Table 13-6.

Francois and Clark (1979) examined the response of 25 ornamental shrub species to irrigation with waters containing either high (7.5 mg/L) or low (2.5 mg/L) B concentrations. Boron tolerance was based on growth reduction and overall plant appearance. The salt tolerance of these species had been established in an earlier study (Bernstein et al. 1972) and no correlation was found between B tolerance and salinity tolerance of the species tested.

Symptoms of boron toxicity. At the early stages, symptoms of salinity and specific ion toxicities in plants are often difficult to distinguish from each other. Foliage may be off-color green with yellowing of the leaf tips or margins. This observation, however, is of little diagnostic value unless accompanied by chemical analysis for specific ions in the tissue. As B in the root environment increases, however, characteristic visual symptoms are evident. Sharp boundaries often distinctly separate the affected and the green unaffected tissues. Leaf margins become scorched and necrotic, and finally the leaf drops prematurely.

Boron toxicity patterns are generally correlated with the venation of the leaf in that chlorosis followed by necrosis appears first at the end of the veins. Parallel-veined leaves (e.g., grasses, lilies) generally show necrosis in leaf tips where the veins terminate. A similar pattern is found in lanceolet leaves (e.g., stock, carnations) where the principal vein terminates in the tip. In species of geranium or broccoli, for example, where veins are of more radial distribution, B toxicity appears as an injured zone

TABLE 13-5. Boron Tolerance Limits for Agricultural Crops

Crop			Boron-Tolerance Parameters		
Common Name (1)	Botanical Name (2)	Tolerance Based On: (3)	Threshold ^a (g m ⁻³) (4)	Slope (% per g m ⁻³) (5)	Rating ^b (6)
Alfalfa	<i>Medicago sativa</i> L.	Shoot DW	4.0–6.0		T
Apricot	<i>Prunus armeniaca</i> L.	Leaf and stem injury	0.5–0.75		S
Artichoke, globe	<i>Cynara scolymus</i> L.	Laminae DW	2.0–4.0		MT
Artichoke, Jerusalem	<i>Helianthus tuberosus</i> L.	Whole plant DW	0.75–1.0		S
Asparagus	<i>Asparagus officinalis</i> L.	Shoot DW	10.0–15.0		VT
Avocado	<i>Persea americana</i> Mill.	Foliar injury	0.5–0.75		S
Barley	<i>Hordeum vulgare</i> L.	Grain yield	3.4	4.4	MT
Bean, kidney	<i>Phaseolus vulgaris</i> L.	Whole plant DW	0.75–1.0		S
Bean, lima	<i>Phaseolus lunatus</i> L.	Whole plant DW	0.75–1.0		S
Bean, mung	<i>Vigna radiata</i> (L.) R. Wilcz.	Shoot length	0.75–1.0		S
Bean, snap	<i>Phaseolus vulgaris</i> L.	Pod yield	1.0	12	S
Beet, red	<i>Beta vulgaris</i> L.	Root DW	4.0–6.0		T
Blackberry	<i>Rubus</i> sp. L.	Whole plant DW	< 0.5		VS
Bluegrass, Kentucky	<i>Poa pratensis</i> L.	Leaf DW	2.0–4.0		MT
Broccoli	<i>Brassica oleracea</i> L. (Botrytis group)	Head FW	1.0	1.8	MS
Cabbage	<i>Brassica oleracea</i> L. (Capitata group)	Whole plant DW	2.0–4.0		MT
Carrot	<i>Daucus carota</i> L.	Root DW	1.0–2.0		MS
Cauliflower	<i>Brassica oleracea</i> L. (Botrytis group)	Curd FW	4.0	1.9	MT
Celery	<i>Apium graveolens</i> L. var. <i>dulce</i> (Mill.) Pers.	Petiole FW	9.8	3.2	VT
Cherry	<i>Prunus avium</i> L.	Whole plant DW	0.5–0.75		S
Clover, sweet	<i>Melilotus indica</i> All.	Whole plant DW	2.0–4.0		MT
Corn	<i>Zea mays</i> L.	Shoot DW	2.0–4.0		MT

Cotton	<i>Gossypium hirsutum</i> L.	Boll DW	6.0–10.0		VT
Cowpea	<i>Vigna unguiculata</i> (L.) Walp.	Seed yield	2.5	12	MT
Cucumber	<i>Cucumis sativus</i> L.	Shoot DW	1.0–2.0		MS
Fig, Kadota	<i>Ficus carica</i> L.	Whole plant DW	0.5–0.75		S
Garlic	<i>Allium sativum</i> L.	Bulb yield	4.3	2.7	T
Grape	<i>Vitis vinifera</i> L.	Whole plant DW	0.5–0.75		S
Grapefruit	<i>Citrus x paradisi</i> Macfady	Foliar injury	0.5–0.75		S
Lemon	<i>Citrus limon</i> (L.) Burm. f.	Foliar injury, Plant DW	< 0.5		VS
Lettuce	<i>Lactuca sativa</i> L.	Head FW	1.3	1.7	MS
Lupine	<i>Lupinus hartwegii</i> Lindl.	Whole plant DW	0.75–1.0		S
Muskmelon	<i>Cucumis melo</i> L. (Reticulatus group)	Shoot DW	2.0–4.0		MT
Mustard	<i>Brassica juncea</i> Coss.	Whole plant DW	2.0–4.0		MT
Oats	<i>Avena sativa</i> L.	Grain (immature) DW	2.0–4.0		MT
Onion	<i>Allium cepa</i> L.	Bulb yield	8.9	1.9	VT
Orange	<i>Citrus sinensis</i> (L.) Osbeck	Foliar injury	0.5–0.75		S
Parsley	<i>Petroselinum crispum</i> Nym.	Whole plant DW	4.0–6.0		T
Pea	<i>Pisum sativa</i> L.	Whole plant DW	1.0–2.0		MS
Peach	<i>Prunus persica</i> (L.) Batsch.	Whole plant DW	0.5–0.75		S
Peanut	<i>Arachis hypogaea</i> L.	Seed yield	0.75–1.0		S
Pecan	<i>Carya illinoensis</i> (Wangenh.) C. Koch	Foliar injury	0.5–0.75		S
Pepper, red	<i>Capsicum annuum</i> L.	Fruit yield	1.0–2.0		MS
Persimmon	<i>Diospyros kaki</i> L. f.	Whole plant DW	0.5–0.75		S
Plum	<i>Prunus domestica</i> L.	Leaf and stem injury	0.5–0.75		S
Potato	<i>Solanum tuberosum</i> L.	Tuber DW	1.0–2.0		MS
Radish	<i>Raphanus sativus</i> L.	Root FW	1.0	1.4	MS
Sesame	<i>Sesamum indicum</i> L.	Foliar injury	0.75–1.0		S
Sorghum	<i>Sorghum bicolor</i> (L.) Moench	Grain yield	7.4	4.7	VT
Squash, scallop	<i>Cucurbita pepo</i> L. var <i>meloepo</i> (L.) Alef.	Fruit yield	4.9	9.8	T
Squash, winter	<i>Cucurbita moschata</i> Poir	Fruit yield	1.0	4.3	MS

(continued)

TABLE 13-5. Boron Tolerance Limits for Agricultural Crops (*Continued*)

Crop			Boron-Tolerance Parameters		
Common Name (1)	Botanical Name (2)	Tolerance Based On: (3)	Threshold ^a (g m ⁻³) (4)	Slope (% per g m ⁻³) (5)	Rating ^b (6)
Squash, zucchini	<i>Cucurbita pepo</i> L. var <i>meloepo</i> (L.) Alef.	Fruit yield	2.7	5.2	MT
Strawberry	<i>Fragaria</i> sp. L.	Whole plant DW	0.75–1.0		S
Sugar beet	<i>Beta vulgaris</i> L.	Storage root FW	4.9	4.1	T
Sunflower	<i>Helianthus annuus</i> L.	Seed yield	0.75–1.0		S
Sweet potato	<i>Ipomoea batatas</i> (L.) Lam.	Root DW	0.75–1.0		S
Tobacco	<i>Nicotiana tabacum</i> L.	Laminae DW	2.0–4.0		MT
Tomato	<i>Lycopersicon lycopersicum</i> (L.) Karst. ex Farw.	Fruit yield	5.7	3.4	T
Turnip	<i>Brassica rapa</i> L. (Rapifera group)	Root DW	2.0–4.0		MT
Vetch, purple	<i>Vicia benghalensis</i> L.	Whole plant DW	4.0–6.0		T
Walnut	<i>Juglans regia</i> L.	Foliar injury	0.5–0.75		S
Wheat	<i>Triticum aestivum</i> L.	Grain yield	0.75–1.0	3.3	S

^aMaximum permissible concentration in soil water without yield reduction. Boron tolerances may vary, depending on climate, soil conditions, and crop varieties.

^bThe B tolerance ratings are based on the following threshold concentration ranges: <0.5 g m⁻³ very sensitive (VS); 0.5–1.0 sensitive (S); 1.0–2.0 moderately sensitive (MS); 2.0–4.0 moderately tolerant (MT); 4.0–6.0 tolerant (T); and >6.0 very tolerant (VT).

Adapted from Maas and Grattan (1999).

TABLE 13-6. Citrus and Stone-Fruit Rootstocks Ranked in Order of Increasing Boron Accumulation and Transport to Scions

Common Name	Botanical Name
Citrus	
Alemow	<i>Citrus macrophylla</i>
Gajanimma	<i>C. pennivesiculata</i> or <i>C. moi</i>
Chinese box orange	<i>Severina buxifolia</i>
Sour orange	<i>C. aurantium</i>
Calamondin	<i>x Citrofortunella mitis</i>
Sweet orange	<i>C. sinensis</i>
Yuzu	<i>C. junos</i>
Rough lemon	<i>C. limon</i>
Grapefruit	<i>C. x paradisi</i>
Rangpur lime	<i>C. x limonia</i>
Troyer citrange	<i>x Citroncirus webberi</i>
Savage citrange	<i>x Citroncirus webberi</i>
Cleopatra mandarin	<i>C. areticulata</i>
Rusk citrange	<i>x Citroncirus webberi</i>
Sunki mandarin	<i>C. reticulata</i>
Sweet lemon	<i>C. limon</i>
Trifoliolate orange	<i>Poncirus trifoliata</i>
Citrumelo 4475	<i>P. trifoliata x C. paradisi</i>
Ponkan mandarin	<i>C. reticulata</i>
Sampson tangelo	<i>C. x Tangelo</i>
Cuban shaddock	<i>C. maxima</i>
Sweet lime	<i>C. aurantiifolia</i>
Stonefruit	
Almond	<i>Prunus duclis</i>
Myrobalan plum	<i>P. cerasifera</i>
Apricot	<i>P. armeniaca</i>
Marianna plum	<i>P. domestica</i>
Shalil peach	<i>P. persica</i>

Adapted from Maas and Grattan (1999).

all around the margin. In leaves with a well-developed network of veins, and with many veins ending in areas between principal side veins (gerberas, asters, eucalyptus, most citrus species), symptoms first develop as interveinal yellow or red spots. As injury progresses, chlorosis spreads to the margins (Oertli and Kohl 1961).

Other B toxicity symptoms commonly observed in landscape plants include terminal twig dieback, necrotic leaf spots, abnormal leaf forms

and texture, and bark cracking. Necrosis associated with B is often black and sometimes red (e.g., eucalyptus) and is most severe on the older foliage (Chapman 1966). Characteristic symptoms of B toxicity in stone-fruit trees are reduction of flower bud formation, poor fruit set, and malformed fruit exceptionally poor flavor (Johnson 1996). In citrus trees, symptoms often progress from tip chlorosis and mottling to the formation of tan-colored, resinous blisters on the underside of the leaves (Wutscher and Smith 1996).

Boron toxicity and how it is expressed by plants is related to some extent on the mobility of B in the plant. Although in most plant species B is thought to be immobile, accumulating in the margins and tips of the oldest leaves, B can be remobilized by some species (Brown and Shelp 1997). These B-mobile plants have high concentrations of polyols (sugar alcohols) that bind with the B and allow it to be mobilized in the shoot. Examples include almonds, apples, grapes, and most stonefruits. For these crops, B concentrations are higher in younger tissue than in older tissue, and injury is expressed in the young, developing tissue. This likely explains symptoms, such as reduced bud formation and twig die-back. Boron-immobile plants, such as pistachios, tomatoes, walnuts, and figs, do not have high concentrations of polyols and the B concentrates in the margins of older leaf tissue. Injury in these crops is expressed as the classical necrosis on leaf tips and margins.

Salinity–boron interactions. Because excess B often occurs in areas with saline soils and waters, it is relevant to consider B uptake by plants under saline conditions inasmuch as B toxicity may be confounded with the associated problems of salt accumulation (Nicholaichuk et al. 1988). Although plant response to high concentrations of B in the root media has been extensively reviewed (Nable et al. 1997), the interactive effects of salinity and B on plant performance have received less attention (Grieve and Poss 2000; Alpaslan and Gunes 2001; Ben-Gal and Shani 2002; Diaz and Grattan 2009; Edelstein et al. 2005; Tripler et al. 2007; Yermiyahu et al. 2007, 2008). Moreover, studies addressing the interaction of the dual stresses on crop response reach widely different conclusions. Bingham et al. (1987) reported that wheat shoot growth was influenced by each stress independently but not by their interaction. Several studies have shown that salt stress may increase B toxicity symptoms and reduce crop yield (Aspaslan and Gunes 2001; Grieve and Poss 2000; Supanjani 2006; Wimmer et al. 2003). Conversely, results of other studies suggest that increased salinity may reduce B uptake and mitigate its toxic effects in wheat (Holloway and Alston 1992), chickpeas (Yadav et al. 1989), melons (Edelstein et al. 2005), and eucalyptus (Grattan et al. 1997; Marcar et al. 1999). Recent research at the USDA-ARS U.S. Salinity Laboratory shows that there are complex interactions among salinity, B, and pH (Grieve et al.

2010; Smith et al. 2010a,b). These new findings suggest that more research is needed to better understand the mechanisms of these interactions.

Selenium and other trace elements

Since the publication of ASA Monograph 38 *Agricultural Drainage* (Skaggs and van Schilfgaarde 1999), environmental concerns related to trace elements have added a new dimension to drainage management and disposal. Certain irrigated soils derived from sedimentary rock materials contain, or at least originally contained, high concentrations of trace elements that dissolve in the soil-water and move to the shallow groundwater. Pratt and Suarez (1990) provide a table that lists the recommended maximum concentration of 15 trace elements in irrigation waters that provide long-term protection of plants and animals. However, the recent concern that these elements pose for irrigated agriculture is not so much their effects on limiting production but rather the toxicological effects they can cause when drainage effluents that contain them are used for irrigation or are discharged into bodies of water. If such effluents are used to supplement irrigation water supplies, certain trace elements may accumulate in the soil and/or crop to levels that pose a health hazard to consumers. Molybdenum (Mo) and selenium (Se) are readily absorbed by plants and can be toxic to animals and humans (Page et al. 1990). If trace-element-tainted drainage effluents are discharged into channels, lakes, ponds, estuaries, or other bodies of water, there are ecological concerns that they may concentrate as they move up the food chain, a process called biomagnification.

The composition of salts in the drainage effluent can influence the uptake of certain trace elements by plants. Selenium, for example, is found in soil solutions in California's San Joaquin Valley, where it exists together with high concentrations of sulfate. Uptake of both SeO_4^{2-} and SO_4^{2-} by plants is mediated by the same high-affinity enzyme, and the anions compete for binding sites on this cell membrane carrier (Läuchli 1993). Plant accession of Se from a substrate high in sulfate will be significantly lower than from a Cl system. Irrigation with drainage water dominated by sulfate salts reduced selenate accumulation in vegetables (Burau et al. 1991), wheat (Grieve et al. 1999), soybeans (Wang et al. 2005), and the seed oil crop lesquerella (Grieve et al. 2001). In some areas where total soil Se is high (5 mg/kg dry wt) and sulfate concentrations are much lower than those in the San Joaquin Valley, plants can accumulate Se to phytotoxic levels, such as the case with wheat grown in an isolated area in the Punjab state of India (G. S. Dhillon, personal communication, 2007).

Selenium accumulation by plants is also influenced by the irrigation method. Although root uptake of Se is inhibited by the presence of sulfate in the external media, a similar interaction apparently does not occur in leaf tissue. Therefore, Se is readily taken up by leaves of forage forage *Brassica*

species (Suarez et al. 2003), Swiss chard, spinach, and soybeans (D. L. Suarez, personal communication) sprinkler-irrigated with Se-containing, sulfate-dominated saline waters. Studies conducted in sand tank cultures have shown that sulfate salinity can also reduce Mo accumulation in alfalfa shoots (Grattan et al. 2004b) but had the opposite effect on tall wheatgrass (cv 'Jose') (Diaz and Grattan 2009).

PARAMETERS INFLUENCING PLANT RESPONSE TO SALT STRESS

Although crop yields are a function of salt concentrations within the rootzone, it must be recognized that this relationship is influenced by interactions between salinity and various soil, water, and climatic conditions. While other environmental stresses may limit crop yield, they may increase, decrease, or have no effect on the apparent salt tolerance of the crop. It is important, therefore, that the effects of any interacting factor be compared on the basis of relative crop yield. Even though expressing the yields on a relative basis minimizes large differences in absolute yield from experiments conducted in different sites and conditions, these factors can still affect the apparent salt tolerance expressed on a relative basis.

Soil water content

Salt-affected crops often must contend with water deficits or excess as well. Therefore, actual crop performance during the growing season is related to how the plant responds to both salinity and water stress. In flooded or poorly drained soils, the overall diffusion of oxygen to roots is reduced, thereby limiting root respiration and plant growth (Sharpley et al. 1992). When the rootzone is saturated with saline water, the combined effects of salinity and oxygen deficiency can adversely affect seed germination (Aceves-N et al. 1975), selective ion transport processes in the plant (Drew et al. 1988; Barrett-Lennard 2003), and shoot growth (Aubertin et al. 1968; Aragüés et al. 2004; Isidoro and Aragüés 2006).

Water deficit, at least to some degree, is practically unavoidable under field conditions, since the soil-water content varies temporally and spatially throughout the season. Exactly how the plant responds to the combination of stresses from salinity and water deficit remains unresolved (Meiri 1984). Obviously the combination of stresses is more damaging than either one alone, but are they additive or antagonistic? Quantifying the growth-limiting contribution of each is difficult, since both change over time and space. Water-deficit stress may predominate in the upper rootzone, while salt stress may predominate in the lower rootzone.

Wadleigh and Ayers (1945) first demonstrated that bean plants responded to the additive combination of water deficit and salt stress. However, Meiri (1984) concluded from data collected by Parra and Romero (1980) that matric potential affected bean shoot growth more than did osmotic potential. Thermodynamically, matric and osmotic components are additive, but resistance to soil water flow must be considered. For example, plant response to these stresses under conditions of low evaporative demand is likely to be different than that observed under high evaporative demand, since matric rather than osmotic potential dominates control of water flow from soil to roots. The magnitude of the difference may be related to differences in evaporative demand and root-length density.

Regardless of how plants respond to integrated stress, they presumably do better when grown on saline soils if water-deficit stress is minimized. However, increasing irrigation frequency does not necessarily improve yields of salt-stressed crops (Bresler and Hoffman 1986; Shalhevet et al. 1982, 1986). Salt-stressed plants are smaller, grow slower than non-salt-stressed plants, and require less water over a given time. Consequently, salt-stressed plants deplete a smaller percentage of available soil water than do nonsaline plants, so they are less responsive to frequent irrigations. Therefore, increased irrigation frequency benefits salt-stressed plants only when it reduces water stress; maintains the salt concentration in the soil solution below growth-limiting levels; and does not contribute to additional stresses, such as O_2 deficit or root disease (e.g., phytophthora). As Wadleigh and Ayers (1945) concluded more than a half a century ago, it is not that salt-stressed plants should necessarily be irrigated more frequently, but rather that they should be irrigated at lower soil-water depletion.

Salt composition. The composition of salts in water varies widely across the globe. In most waters, the dominant cations are Na^+ , Ca^{2+} , and Mg^{2+} , while the dominant anions are Cl^- , SO_4^{2-} , and HCO_3^- (Grattan and Grieve 1999). Most horticultural crops are subjected to irrigation water or soil solutions with $Na^+/(Na^+ + Ca^{2+})$ in the range of 0.1 to 0.7, suggesting that the composition of saline water employed in experimental studies should reflect this ratio. Despite recommendations by early investigators of plant salt tolerance that plants under salt stress require higher concentrations of Ca^{2+} than under nonsaline conditions (Hayward and Wadleigh 1949; Pearson 1959; Hayward and Bernstein 1958; Bernstein 1975), a high percentage of salinity studies of agronomic and horticultural crops continue to be conducted with NaCl as the sole salinizing agent. The use of this unrealistic salinizing composition may induce ion imbalances that contribute to Na-induced Ca^{2+} deficiencies and Ca-related physiological disorders in certain susceptible crops (Shear 1975; Maas and Grieve 1987;

Sonneveld 1988; Suarez and Grieve 1988). Furthermore, the use of single-salt solutions in salt-tolerance experiments may result in misleading and erroneous interpretations about plant response to salinity.

A similar argument can be offered for the anions. Although the majority of salinity studies use Cl^- as the sole salinizing anion, most soil solutions contain a high proportion of SO_4^{2-} and HCO_3^- . Plants can perform equally well with moderate variations in the $\text{Cl}^-/\text{SO}_4^{2-}$ ratio, but at measurably low ratios at the same salinity level, some plants perform better in the sulfate-dominated solutions. Bicarbonate is somewhat different from Cl^- or SO_4^{2-} because it can be damaging under even mildly saline conditions when it is the dominant anion. It is likely that more can be learned if future salinity-nutrition studies, regardless of experimental scale or objectives, are conducted with more realistic ion ratios.

Much of the salt-tolerance information has been derived from studies of plant responses to Cl-dominated saline irrigation waters that typically contain both NaCl and CaCl_2 . A few research teams have evaluated plant salt tolerance by using irrigation waters prepared to simulate recycled or saline waters typical of a specific location or site. Dutch growers frequently employ solutions with compositions adjusted to the average salt composition of surface waters in the western region of the Netherlands (Bik 1980; Sonneveld 1988). Saline waters ($\text{EC} = 2.5$ to 4.5 dS m^{-1}) from local wells in Israel continue to be used successfully for cut-flower production on more than 700 ha throughout the Negev Desert (Shillo et al. 2002). Arnold and coworkers (2003) demonstrated that recycled runoff effluents from a nursery operation and water from a constructed wetland were suitable for irrigating certain bedding and cut-flower crops. Irrigation waters used in recent research at the U.S. Salinity Laboratory were prepared to mimic waters available at three locations within California: (1) Na^+ - and SO_4^{2-} -dominated drainage effluents present in the San Joaquin Valley (Grattan et al. 2004a,b; Grieve et al. 2005; Skaggs et al. 2006a,b); (2) compositions of increasing salinity that would result from concentration of Colorado River waters (Grieve et al. 2006); and (3) waters affected by seawater intrusion along the California coastal areas (Carter et al. 2005; Carter and Grieve 2008).

Soil biota

Full coverage of the interactions of salinity and soil flora and fauna is clearly beyond the scope of this chapter. However, the importance of soil organisms cannot be ignored. The use of controlled mycorrhization has been shown to alleviate deleterious effects of salt stress and improve yields of tomatoes (Al-Karaki 2006), lettuce (Ruiz-Lozano et al. 1996), sorghum (Cho et al. 2006), and bananas (Yano-Melo et al. 2003). *Rhizobium* spp., which are integral to legume production, seem more salt-tolerant than

their host plants, but evidence indicates that nodulation and N_2 fixation by some crops are impaired by salinity (Läuchli 1984). Growth of several legumes was reduced more when grown symbiotically than with N fertilization. Some investigators have suggested that mycorrhizal symbioses improve the ability of some crops to tolerate salt by improving P nutrition (Hirrel and Gerdemann 1980; Ojala et al. 1983; Poss et al. 1985) or by enhancing K:Na status (Sannazzaro et al. 2006).

Although salinity does not specifically cause plant diseases, salt-stressed plants may be predisposed to infection by soil pathogens. Salinity has been reported to increase the incidence of phytophthora root rot in chrysanthemums (MacDonald 1982), citrus (Blaker and MacDonald 1986), chili peppers (Sanogo 2004), and tomatoes (Snapp et al. 1991); the colonization of pistachios (Mohammadi et al. 2007) and olives (Levin et al. 2007) rootstocks by *Verticillium dahlia*; and the incidence and severity of crown and root rot of tomatoes by *Fusarium oxysporum* (Triky-Dotan et al. 2005). The combined effects significantly reduced fruit size and yield of tomatoes (Snapp et al. 1991). Wetter soil under salt-stunted plants may contribute to increased susceptibility to fungal diseases. Inadequate drainage could exacerbate this condition.

Soil fertility

In irrigated agriculture, fields are usually fertilized to achieve maximum productivity. Sometimes fertilizer applications are inadequate or even omitted because of cost or availability. If crops are grown on low-fertility soils, they may seem more salt-tolerant than those grown with adequate fertility. The reason is that fertility, not salinity, is the primary factor limiting plant growth. Proper fertilizer applications would increase yields whether or not the soil was saline but proportionately more if it were nonsaline. The results of Bernstein et al. (1974) indicate that the effects of salinity and nutritional stresses tend to be additive, provided that neither of these stresses are extreme. When yields are limited similarly by salinity and infertility, the effects of decreasing salinity or increasing fertility will give similar benefits. However, if yields are reduced much more by one factor than the other, alleviating the most severe condition will increase yield more than alleviating the less restrictive condition.

Therefore, one must be careful in interpreting salinity $\times$ fertility studies in terms of whether fertilizer additions increase or decrease crop salt tolerance. Response functions are based on relative crop yield as salinity increases from non-growth-limiting to severely growth-limiting levels (Maas and Grattan 1999). Although suboptimal soil fertility may be the most growth-limiting factor at low salinity, salt stress may be the most growth-limiting at higher salinity levels with the same level of fertility (Grattan and Grieve 1994). Therefore, depending on the

severity of salt stress, fertilizer additions may increase or decrease crop salt tolerance.

Although crop salt tolerance is expressed on a relative basis, actual yields must be considered in evaluating the benefits of fertilizer. For example, fertilizer additions may decrease crop salt tolerance, but it still may be economically advantageous to fertilize if absolute yields are increased. However, unless salinity causes specific nutritional imbalances, fertilizer applications exceeding that required under nonsaline conditions have rarely been beneficial in alleviating growth inhibition by salinity. Most studies indicate that excess N, P, and K applications have little effect or that they reduce salt tolerance (Grattan and Grieve 1994); however, Ravikovitch and Yoles (1971) found that N, P, or both seemed to increase the salt tolerance of millet and clover.

Reliable data on the salt tolerance of crops during emergence and seedling growth are extremely limited (Maas and Grieve 1994). Although salt stress may delay emergence, the final emergence percentage for most crops is not affected if salt concentrations remain at or below the tolerance threshold for mature yields. No systematic evaluation of the tolerance of crop seedlings grown under actual or simulated field conditions has ever been undertaken. Clearly, more research is needed to better understand how crops respond to integrated stresses they encounter between germination and emergence.

Irrigation methods

The method of irrigation can affect the crop's response to salinity. The irrigation method (1) influences the salt distribution in the soil, (2) determines whether leaves will be subjected to wetting, and (3) determines the ease at which high soil-water potentials can be achieved (Bernstein and Francois 1973; Shalhevet 1984). Since irrigation methods that maintain a higher soil-water potential reduce the time-averaged salt concentration in the soil-water, they allow for optimal plant performance.

With pressurized systems, such as drip and sprinkler, small applications of water can be applied to fields uniformly, unlike surface irrigation methods, such as furrow, basin, or flood. Surface irrigation systems require some minimum quantity of water to enable uniform applications over the field. This minimum quantity may be in excess of the yield-threshold soil-water depletion, thereby resulting in unnecessary drainage losses. Therefore, pressurized systems (sprinkler, drip, etc.) are more conducive for light, uniform irrigations.

Although irrigating at lower soil-water depletion (i.e., higher matric potential) may be desirable to maintain a favorable soil-water environment, use of sprinkler irrigation to achieve this creates an additional problem. Salts in the irrigation water can be readily absorbed by wetted foliage

and cause foliar injury. This subject will be addressed in more detail later in this section.

In light of this discussion, it is not surprising that crop salt tolerance has been found to vary under different irrigation methods (Bernstein and Francois 1973; Bernstein and Francois 1975; Meiri et al. 1982), where crop performance was best under drip irrigation and worst under sprinkler irrigation.

Salt distribution patterns, such as those described, are related to the combined effects of root water extraction patterns and the net direction of water flow in the soil. Salt accumulation is lowest at the point in the soil where irrigation water contacts the soil but increases in the direction of soil water flow. Water moves in the direction where it is transpired or evaporated, thereby concentrating salts in areas where it occurs (Kruse et al. 1990). Salt accumulation patterns under furrow, sprinkler, drip, and subsurface drip irrigation methods have been described by Oster et al. (1984) and Wang et al. (2002). Subsurface drip irrigation practices can create unique salt accumulation patterns where salts accumulate in the soil above the drip line (Hanson et al. 2009). Plant roots encounter unexpected salination when rain moves salts accumulated at the soil surface back into the rootzone.

PLANT TOLERANCE TO SALINE SPRINKLING WATERS

Sprinkler-irrigated crops are subject to additional salt damage when the foliage is wetted by saline water. Salts are directly accumulated by the leaves and, as a result, some species become severely injured and lose their leaves. Of course, sprinkler-irrigated crops are subject to injury from both soil salinity and salt spray. Any genetically controlled mechanisms that may have evolved in plants to restrict Na^+ and Cl^- from the shoot may become irrelevant under sprinkler irrigation. The degree of injury is related to the salt concentration in the leaves, but weather conditions and water stress can influence the onset of injury. For instance, leaves may contain toxic levels of Na^+ or Cl^- for several weeks without exhibiting any injury symptoms, but the first hot, dry weather will cause severe leaf necrosis. Consequently, there are no practical guidelines for correlating foliar injury to salt concentrations in the leaves.

Obviously, saline irrigation water is best distributed through surface distribution systems. However, if sprinkling with marginally saline water cannot be avoided, several precautions should be considered (Maas 1986). If possible, susceptible crops should be irrigated below the plant canopy to eliminate or reduce wetting of the foliage. Since injury is related more to the number of sprinklings than to their duration, infrequent, heavy irrigations would be preferable to frequent, light irrigations. Intermittent

wetting by slowly rotating sprinklers that allow drying between cycles should be avoided. Lateral sprinkler systems might be moved downwind, when possible, so that salts accumulated on the leaves from salt drift would be washed off as the sprinkler moves past. Perhaps the best strategy for minimizing foliar injury to plants is to irrigate at night when both evaporation and salt absorption are reduced. Daytime sprinkling should be avoided on hot, dry, windy days.

Sprinkling with low-salinity water for 3 to 5 minutes either prior to or after sprinkler irrigations with saline water effectively reduced foliar salt accumulation and injury in barley and corn (Aragüés et al. 1994; Benes et al. 1996). These investigators concluded that much of the salt accumulated by wetted leaves is absorbed during the first few minutes of irrigation and also after sprinkling when the saline water evaporates and concentrates on the leaf surface. Sprinkling barley with 9.6 dS m^{-1} water, for example, reduced grain yields by 58% compared to nonsprinkled plants, but when saline-sprinkled plants received both pre- and post-washing with nonsaline water, yields were reduced only 17% (Benes et al. 1996). The soil surface was covered to shed the sprinkling waters in all cases. Post-rinsing of soybean plants with nonsaline water prevented leaf injury due to potentially toxic levels of Cl^- (Wang et al. 2002; Grieve et al. 2003). In this field trial, the soil surface was not covered; therefore, Cl^- and other ions were accumulated via both the root pathway and foliar absorption. This information may be useful to growers who have access to and can readily switch between sources of irrigation waters of different quality.

CONTROLLING SOIL SALINITY

Most of the crop salt-tolerance data provided in Tables 13-1 and 13-2 reflect how the plant responds to a relatively uniform soil-salinity profile from the established seedling stage to harvest. Although useful, particularly for crop comparison purposes, field-grown crops respond to salinity profiles that change over time, making relative yield predictions understandably difficult. There are advantages, however, in imposing water management practices that allow salinity profiles to change over time, as opposed to maintaining relatively constant soil salinity profiles. With controlled changes in soil salinity, crops with different tolerances to salinity can be included within a crop rotation (Rhoades et al. 1988, 1989). Increases in soil salinity are also acceptable when the tolerance of a crop increases within a season (Shennan et al. 1995; Steppuhn et al. 2009). Adequate control of soil salinity changes requires that the farmer has access to multiple and dependable supplies of irrigation water where at least one supply is of good quality. Within limits, farmers who have irrigation water supplies of different qualities can use them alter-

nately (cyclically) in different years or at different times of the year, or they can blend supplies to achieve a suitable quality water (Grattan and Rhoades 1990).

Regardless of the irrigation water supplies and quality available to the grower, irrigation practices must be managed to control soil salinity within an acceptable level. This requires that a favorable salt balance be attained. This does not suggest, however, that a calculated leaching requirement must be achieved each irrigation. Leaching fractions (LFs) often decrease as the season progresses. In fact, a reduced LF is a consequence of a mature, deep-rooted crop actively growing in a soil with low permeability during months of high evaporative demand. Prolonged periods of saturation required to achieve leaching could produce anoxic conditions and encourage root disease. Nevertheless, a favorable salt balance must be maintained, even if intermittent leaching (e.g., during the winter, alternate years) is the only means to remove excess salts from the soil.

A long-term salt balance can only be achieved at the farm scale if there is adequate drainage beyond the rootzone. Crops grown in areas affected by rising saline water tables are subjected to salination. Crop production in these situations cannot be sustained indefinitely, since a long-term salt balance cannot be achieved. Use of saline water to irrigate crops grown in soils with high water tables accelerates the problem. Moreover, the required leaching further raises the saline water table, thereby salinizing the rootzone even more. This paradox can only be overcome by adequate drainage and disposal, thereby ensuring that crop yields can be sustained over the long term (van Schilfgaarde 1990).

SUMMARY

In making decisions about salinity management and the use of low-salinity irrigation water, there are a number of variables that a grower may consider. First is that the published threshold and slope values for various crops represent statistical means, not absolute values, and actual crop tolerance falls within a range around these means. Crop selection should therefore include consideration of the relative total production of a crop, since a high-production crop may have a net economic yield high enough to offset the effects of salinity stress. In addition, there are some potential crop-specific benefits of high-salinity environments, such as increases in sugars, total soluble solids, postharvest handling characteristics, and the concentration of various flavonoids, ascorbates, tocopherols, carotinoids, and lycopene. For ornamental species, the visible effects of salt stress may also not affect the aesthetics of the plant, and salt stress effects may have benefits, such as low growth and low water uptake. Salt-tolerant plants

(halophytes) may also be planted for a combination of their crop value and their value in treating drainage and other wastewater.

In addition, there are plant-specific effects of high-salinity environments on nutrient uptake; for example, high sodium levels may inhibit plant uptake of Ca^{2+} . The grower may wish to consider the plant-specific effects of the specific salt composition of the field on the proposed crop and adjust cropping accordingly. Finally, salt stress may be affected by soil-water content, salt composition, soil biota, soil fertility, irrigation method, and timing of irrigation. Management of these variables may reduce the cumulative stresses on a crop and thus minimize the net impact of salt stress.

REFERENCES

- Abel, G. H., and MacKenzie, A. J. (1964). "Salt tolerance of soybean varieties (*Glycine max* L. Merrill) during germination and later growth." *Crop Sci.*, 4, 157–161.
- Aceves-N., E., Stolzy, L. H and Mehuys, G. R. (1975). "Combined effects of low oxygen and salinity on germination of semi-dwarf Mexican wheat." *Agron. J.*, 67, 530–532.
- Adams, P., and Ho, L. C. (1989). "Effects of constant and fluctuating salinity on the yield, quality and calcium status of tomatoes." *J. Hort. Sci.*, 64, 725–732.
- Al-Karaki, G. N. (2006). "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water." *Sci. Hort.*, 109, 1–7.
- Alpaslan, M., and Gunes, A. (2001). "Interactive effects of boron and salinity stress on the growth, membrane permeability and mineral composition of tomato and cucumber plants." *Plant Soil*, 236, 123–128.
- Aragüés, R., Puy, J., and Isidoro, D. (2004). "Vegetative growth response of young olive trees (*Olea europaea* L., cv. Arbequina) to soil salinity and waterlogging." *Plant Soil*, 258, 69–80.
- Aragüés, R., Puy, J., Royo, A., and Espada J. L. (2005). "Three-year field response of young olive trees (*Olea europaea* L., cv. Arbequina) to soil salinity: Trunk growth and leaf ion accumulation." *Plant Soil*, 271, 265–271.
- Aragüés, R., Royo, A., and Grattan, S. R. (1994). "Foliar uptake of sodium and Cl in barley sprinkler-irrigated with saline water. Effect of pre-irrigation with fresh water." *Eur. J. Agron.*, 3, 9–16.
- Arnold, M. A., Lesikar, B. J., McDonald, G. V., Bryan, D. L., and Gross, A. (2003). "Irrigating landscape bedding plants and cut flowers with recycled nursery runoff and constructed wetland treated water." *J. Environ. Hort.*, 21, 89–95.
- Aronson, J. A. (1989). *HALOPH: A database of salt tolerant plants of the world*, Office of Arid Lands Studies, University of Arizona Press, Tucson, Ariz.
- Ashraf, M., and Harris, P. J. C. (2004). "Potential biochemical indicators of salinity tolerance in plants." *Plant Sci.*, 166, 3–16.
- Aubertin, G. M., Rickman, R.W., and Letey, J. (1968). "Differential salt-oxygen levels influence plant growth." *Agron. J.*, 60, 345–349.

- Awad, A. S., Edwards, D. G., and Campbell, L. C. (1990). "Phosphorus enhancement of salt tolerance of tomato." *Crop Sci.*, 30, 123–128.
- Ayers, A. D., and Eberhard, D. L. (1960). "Response of edible broadbean to several levels of salinity." *Agron. J.*, 52, 110–111.
- Ayers, R. S., and Westcot, D. W. (1985). *Water quality for agriculture*, FAO Irrigation and Drainage Paper 29, Rev. 1, Food and Agriculture Organisation of the United Nations, Rome.
- Bangerth, F. (1979). "Calcium-related physiological disorders of plants." *Ann. Rev. Plant Physiol.*, 97, 1136–1145.
- Barrett-Lennard, E. G. (2003). "The interaction between waterlogging and salinity in higher plants: Causes, consequences and implication." *Plant Soil*, 253, 35–54.
- Bartosz, G. (1997). "Oxidative stress in plants." *Acta Physiol. Plant.*, 19, 47–64.
- Benes, S. E., Aragüés, R., Austin, R. B., and Grattan, S. R. (1996). "Brief pre- and post-irrigation sprinkling with freshwater reduces foliar salt uptake in maize and barley sprinkler irrigated with saline water." *Plant Soil*, 180, 87–95.
- Ben-Gal, A., and Shani, U. (2002). "Yield, transpiration and growth of tomatoes under combined excess boron and salinity stress." *Plant Soil*, 247, 211–221.
- Bernstein, L. (1962). "Salt-affected soils and plants," in *Problems in arid zones, Proc., 18th UNESCO Symp.*, Paris, 139–174.
- . (1964). *Salt tolerance of plants*, USDA Information Bulletin 283, U.S. Government Printing Office, Washington, D.C.
- . (1975). "Effects of salinity and sodicity on plant growth." *Ann. Rev. Phytopath.*, 13, 295–312.
- Bernstein, L., and Ayers, A. D. (1953). "Salt tolerance of five varieties of carrots." *Proc. Am. Soc. Hort. Sci.*, 67, 367–370.
- Bernstein, L., Ayers, A. D., and Wadleigh, C. H. (1951). "The salt tolerance of White Rose potatoes." *Am. Soc. Hort. Sci.*, 57, 231–236.
- Bernstein, L., Brown, J. W., and Hayward, H. E. (1956). "Influence of rootstock on growth and salt accumulation in stone-fruit trees and almonds." *Proc. Am. Soc. Hort. Sci.*, 68, 86–95.
- Bernstein, L., Ehling, C. F., and Clark, R. A. (1969). "Effect of grape rootstocks on Cl accumulation in leaves." *J. Amer. Soc. Hort. Sci.*, 84, 584–590.
- Bernstein, L., and Francois, L. E. (1973). "Comparison of drip, furrow, and sprinkler irrigation." *Soil Sci.*, 115, 73–78.
- . (1975). "Effects of frequency of sprinkling with saline waters compared with daily drip irrigation." *Agron. J.*, 67, 185–190.
- Bernstein, L., Francois, L. E., and Clark, R. A. (1972). "Salt tolerance of ornamental shrubs and ground covers." *J. Am. Soc. Hort. Sci.*, 97, 550–556.
- . (1974). "Interactive effects of salinity and fertility on yields of grains and vegetables." *Agron. J.*, 66, 412–421.
- Bik, R. A. (1980). "Effect of irrigation water salinity on postharvest performance of cyclamen grown on rockwool and potting compost." *Act Hort.*, 99, 189–196.
- Bingham, F. T., Strong, J. E., Rhoades J. D., and Keren, R. (1985). "An application of the Maas-Hoffman salinity response model for boron toxicity." *Soil Sci. Soc. Am. J.*, 49, 672–674.
- . (1987). "Effects of salinity and varying boron concentrations on boron uptake and growth of wheat." *Plant Soil*, 97, 345–351.

- Blaker, N. S., and MacDonald, J. D. (1986.) "The role of salinity in the development of *Phytophthora* root rot of citrus." *Phytopathology*, 76, 970–975.
- Botia, P., Navarro, J. M., Cerdá, A., and Martinez, V. (2005). "Yield and fruit quality of two melon cultivars irrigated with saline water at different stages of development." *Europ. J. Agron.*, 23, 243–253.
- Bresler, E., and Hoffman, G. J. (1986.) "Irrigation management for soil salinity control: Theories and tests." *Soil Sci. Soc. Am.*, J. 50, 1552–1560.
- Brown, P. H., and Shelp, B. J. (1997). "Boron mobility in plants." *Plant Soil*, 193, 85–101.
- Burau, R. G., Shennan, C., May, D., and Grattan, S. (1991). *Uptake of boron and selenium by vegetables grown in the field as affected by boric acid, selenate and sulfate levels in irrigation water and the impact on the diets of consumers, 1990–1991*, University of California Salinity/Drainage Task Force Technical Progress Report, University of California Division of Agricultural and Natural Resources.
- Cabrera, R. I. (2000). "Evaluating yield and quality of roses with respect to nitrogen fertilization." *Acta Hort.*, 511, 133–142.
- Cabrera, R. I., and Perdomo, P. (2003). "Reassessing the salinity tolerance of greenhouse roses under soilless production conditions." *Hort. Sci.*, 38, 533–536.
- Campos, C. A. B., Fernandes, P. D., Gheyi, H. R., Blanco, F. F., and Campos, S. A. F. (2006). "Yield and fruit quality of industrial tomato under saline irrigation." *Sci. Agric.*, 63, 146–152.
- Carter, C. T., and Grieve. C. M. (2008). "Mineral nutrition, growth, and germination of *Antirrhinum majus* L. (snapdragon) when produced under increasingly saline conditions." *Hort. Sci.*, 43, 710–718.
- Carter, C. T., Grieve, C. M., Poss, J. A., and Suarez, D. L. (2005). "Production and ion uptake of *Celosia argentea* irrigated with saline wastewaters." *Sci. Hort.*, 106, 381–394.
- Carter, M. R., Webster, G. R., and Cairns, R. R. (1979). "Calcium deficiency in some solonchic soils of Alberta." *J. Soil Sci.*, 30, 161–174.
- Catlin, P. B., Hoffman, G. J., Mead, R. M., and Johnson, R. S. (1993). "Long-term response of mature plum trees to salinity." *Irrig. Sci.*, 13, 171–176.
- Chang, P. T., and Randle, W. M. (2005). "Sodium Cl timing and length of exposure affect onion growth and flavor." *J. Plant Nutr.*, 28, 1755–1766.
- Chapman, H. D. (1966). *Diagnostic criteria for plants and soils*, University of California Division of Agricultural and Natural Resources, Oakland, Calif.
- Chartzoulakis, K. S. (1992). "Effects of NaCl salinity on germination, growth and yield of greenhouse cucumber." *J. Hort. Sci.*, 67, 115–119.
- Cho, K. M., Toler, H., Lee, J., Ownley, B., Stutz, J. C., Moore, J. L., and Auge, R. M. (2006). "Mycorrhizal symbiosis and response of sorghum plants to combined drought and salinity stresses." *J. Plant Physiol.*, 163, 517–528.
- Colla, G., Roupahel, Y., Cardarelli, M., and Rea, E. (2006). "Effect of salinity on yield, fruit quality, leaf gas exchange and mineral composition of grafted watermelon plants." *Hort. Sci.*, 41, 622–627.
- Cooper, W. C. (1951). "Salt tolerance of avocado on various rootstocks." *Texas Avocado Soc. Yearbook*, 4, 24–28.
- . (1961). "Toxicity and accumulation of salts in citrus trees on various rootstocks in Texas." *Florida State Hort. Soc. Proc.*, 74, 95–104.

- Costello, L. R., Perry, E. J., Matheny, N. P., Henry, J. M., and Geisel, P. M. (2003). *Abiotic disorders of landscape plants: A diagnostic guide*, Publication 3420, University of California Division of Agricultural and Natural Resources.
- Cuartero, J., and Fernández-Muñoz, R. (1999). "Tomato and salinity." *Sci. Hort.*, 78, 83–125.
- De Pascale, Maggio, A., Fofliano, V., Ambrosino, P., and Ritieni, A. (2001). "Irrigation with saline water improves carotenoids content and antioxidant activity of tomato." *J. Hort. Sci. Biotech.*, 76, 447–453.
- Diaz, F. J., and Grattan, S. R. (2009). "Performance of tall wheatgrass (*Thinopyrum ponticum*, cv. 'Jose') irrigated with saline-high boron drainage water: Implications on ruminant mineral nutrition." *Agri. Ecosystems Environ.*, 131, 128–136.
- Drew, M. C., Guenther, J., and Läuchli, A. (1988). "The combined effects of salinity and root anoxia on growth and net Na⁺ and K⁺ accumulation in *Zea mays* grown in solution culture." *Ann. Bot.*, 61, 41–43.
- Eaton, F. M. (1944). "Deficiency, toxicity, and accumulation of boron in plants." *J. Agric. Res.*, 69, 237–277.
- Edelstein, M., Ben-Hur, M., Cohen, R., Burger, Y., and Ravina, I. (2005). "Boron and salinity effects on grafted and non-grafted melon plants." *Plant Soil*, 269, 73–284.
- Ehlig, C. F. (1960). "Effects of salinity on four varieties of table grapes grown in sand culture." *Proc. Am. Soc. Hort. Sci.*, 76, 323–331.
- Farnham, D., Ayers, R. S., and Hasek, R. F. (1985). *Water quality: Its effect on ornamental plants*, Leaflet 2995, University of California Division of Agricultural and Natural Resources.
- Ferguson, L., Poss, J. A., Grattan, S. R., Grieve, C. M., Wang, D., Wilson, C., Donovan, T. J., and Chao, C.-T. (2002). "Pistachio rootstocks influence scion growth and ion relations under salinity and boron stress." *J. Am. Soc. Hort. Sci.*, 127, 194–199.
- Francois, L. E. (1984). "Effect of excess boron on tomato yield, fruit size, and vegetative growth." *J. Am. Soc. Hort. Sci.*, 109, 322–324.
- . (1986). "Effect of excess boron on broccoli, cauliflower and radish." *J. Am. Soc. Hort. Sci.*, 111, 484–498.
- . (1987). "Salinity effects on asparagus yield and vegetative growth." *J. Am. Soc. Hort. Sci.*, 112, 432–436.
- . (1988). "Yield and quality responses of celery and crisphead lettuce to excess boron." *J. Am. Soc. Hort. Sci.*, 113, 538–542.
- . (1989). "Boron tolerance of snapbean and cowpea." *J. Am. Soc. Hort. Sci.*, 114, 615–619.
- . (1991). "Yield and quality responses of garlic and onion to excess boron." *Hort. Sci.*, 26, 547–549.
- . (1992). "Effect of excess boron on summer and winter squash." *Plant Soil*, 147, 163–170.
- . (1995). "Salinity effects on bud yield and vegetative growth of artichoke (*Cynara scolymus* L.)." *Hort. Sci.*, 30, 69–71.
- Francois, L. E., and Clark, R. A. (1979). "Boron tolerance of twenty-five ornamental shrub species." *J. Am. Soc. Hort. Sci.*, 104, 319–322.
- Francois, L. E., Donovan, T. J., Lorenz, K., and Maas, E. V. (1989). "Salinity effects on rye grain yield, quality, vegetative growth, and emergence." *Agron. J.*, 81, 707–712.

- Francois, L. E., Maas, E. V., Donovan, T. J., and Youngs, V. L. (1986). "Effect of salinity on grain yield and quality, vegetative growth, and germination of semi-dwarf and durum wheat." *Agron. J.*, 78, 1053–1058.
- Francois, L. E., and West, D. W. (1982). "Reduction in yield and market quality of celery caused by soil salinity." *J. Am. Soc. Hort. Sci.*, 107, 952–954.
- Garcia-Sanchez, F., Perez-Perez, F. G., Botia, P., and Martinez, V. (2006). "The response of young mandarin trees grown under saline conditions depends on the rootstock." *Eur. J. Agron.*, 24, 129–139.
- Geraldson, C. M. (1957). "Factors affecting calcium nutrition of celery, tomato, and pepper." *Soil Sci. Soc. Proc.*, 21, 621–625.
- Gersberg, R. M., Elkins, B. V., Lyon, S. R., and Goldman, C. R. (1986). "Role of aquatic plants in wastewater treatment by artificial wetlands." *Water Res.*, 20, 363–368.
- Grattan, S. R., and Grieve, C. M. (1994). "Mineral nutrient acquisition and response by plants grown in saline environments," in *Handbook of plant and crop stress*, M. Pessarakli, ed., Marcel Dekker Inc., New York, 203–226.
- . (1999). "Salinity-mineral nutrient relations in horticultural crops." *Sci. Hort.*, 78, 127–157.
- Grattan, S. R., Grieve, C. M., Poss, J. A., Robinson, P. H., Suarez, D. L., and Benes, S. E. (2004a). "Evaluation of salt-tolerant forages for sequential water reuse systems. I. Biomass production." *Agric. Water Mgmt.*, 70, 109–120.
- . (2004b). "Evaluation of salt-tolerant forages for sequential water reuse systems. III. Potential implications for ruminant nutrition." *Agric. Water Mgmt.*, 70, 137–150.
- Grattan, S. R., and Rhoades, J. D. (1990). "Irrigation with saline groundwater and drainage water," in *Agricultural salinity assessment and management*, K. K. Tanji, ed., ASCE Manuals and Reports on Engineering Practice No. 71, ASCE, Reston, Va., 432–449.
- Grattan, S. R., Shannon, M. C., Grieve, C. M., Poss, J. A., Suarez, D. L., and Francois, L. E. (1997). "Interactive effects of salinity and boron on the performance and water use of eucalyptus." *Acta Hort.*, 449, 607–613.
- Grattan, S. R., Zeng, L., Shannon, M. C., and Roberts, S. R. (2002). "Rice is more sensitive to salinity than previously thought." *Calif. Agric.*, 56, 189–195.
- Grieve, C. M. (2010). "Salinity-induced enhancement of horticultural crop quality," in *Handbook of plant and crop stress*, M. Pessarakli, ed., CRC Press, Boca Raton, Fla., 1175–1196.
- Grieve, C. M., and Maas, E. V. (1988). "Differential effects of sodium:calcium ratio on sorghum genotypes." *Crop Sci.*, 29, 659–665.
- Grieve, C. M., and Poss, J. A. (2000). "Wheat response to interactive effects of boron and salinity." *J. Plant Nutr.*, 23, 1217–1226.
- Grieve, C. M., Poss, J. A., and Amrhein, C. (2006). "Response of *Matthiola incana* to irrigation with saline wastewaters." *Hort. Sci.*, 41, 119–123.
- Grieve, C. M., Poss, J. A., Grattan, S. R., Shouse, P. J., Lieth, J. H., and Zeng, L. (2005). "Productivity and mineral nutrition of *Limonium* species irrigated with saline wastewaters." *Hort. Sci.*, 40, 654–658.
- Grieve, C. M., Poss, J. A., Grattan, S. R., Suarez, D. L., and Smith, T. T. (2010). "The combined effects of salinity and excess boron on mineral ion relations in broccoli." *Sci. Hort.*, 125, 178–187.

- Grieve, C. M., Poss, J. A., Suarez, D. L., and Dierig, D. A. (2001). "Lesquerella growth and selenium uptake affected by saline irrigation water composition." *Ind. Crops Prod.*, 13, 57–65.
- Grieve, C. M., Suarez, D. L., and Shannon, M. C. (1999). "Effect of saline irrigation water composition on selenium accumulation by wheat." *J. Plant Nutr.*, 22, 1443–1450.
- Grieve, C. M., Wang, D., and Shannon, M. C. (2003). "Salinity and irrigation method affect mineral ion relations in soybean." *J. Plant Nutr.*, 26, 901–913.
- Groot Obbink, J., and Alexander, D. M. (1973). "Response of six grapevine cultivars to a range of Cl concentrations." *Am. J. Enol. Viticult.*, 24, 65–68.
- Gupta, U. C., Jaime, Y. W., Campbell, C. A., Leyshon, A. J., and Nicholaichuk, W. (1985). "Boron toxicity and deficiency: A review." *Can. J. Soil Sci.*, 65, 381–409.
- Hanson, B. R., May, D. E., Šimůnek, J., Hopmans, J. W., and Hutmacher, R. B. (2009). "Drip irrigation provides the salinity control needed for profitable irrigation of tomatoes in the San Joaquin Valley." *Calif. Agric.*, 63(3), 131–136.
- Hanson, J. B. (1983). "The roles of calcium in plant growth." *Curr. Topics Plant Biochem. Physiol.*, 1, 1–24.
- Hayward, H. E., and Bernstein, L. (1958). "Plant-growth relationships on salt-affected soils." *Bot. Rev.*, 24, 584–635.
- Hayward, H. E., and Wadleigh, C. H. (1949). "Plant growth on saline and alkali soils." *Adv. Agron.*, 1, 1–38.
- Hirrel, M. C., and Gerdemann, J. W. (1980). "Improved growth of onion and bell pepper in saline soils by two vesicular-arbuscular mycorrhizal fungi." *Soil Sci. Soc. Am. J.*, 44, 654–655.
- Holloway, R. E., and Alston, A. M. (1992). "The effects of salt and boron on growth of wheat." *Aust. J. Agric. Res.*, 43, 987–1001.
- Ibekwe, A. M., Grieve, C. M., and Lyon, S. R. (2003). "Characterization of microbial communities and composition in constructed dairy wetland wastewater effluent." *App. Environ. Microbiol.*, 69, 5060–5069.
- Ibekwe, A. M., Lyon, S. R., Leddy, M., and Jacobson-Meyers, M. (2007). "Impact of plant density and microbial composition on water quality from a free water surface constructed wetland." *J. Appl. Microbiol.*, 102, 921–936.
- Isidoro, D., and Aragüés, R. (2006). "Modeling survival of young olive trees (*Olea europaea* L. cv. Argequino) to saline and waterlogging field conditions." *Agron. J.*, 98, 795–799.
- Janzen, H. H., and Chang, C. (1987). "Cation nutrition of barley as influenced by soil solution composition in a saline soil." *Can. J. Soil Sci.*, 67, 619–629.
- Johnson, R. S. (1996). "Stone fruit: Peaches and nectarines," in *Nutrient deficiencies and toxicities in crop plants*, W. F. Bennett, ed., The American Phytopathology Society, St. Paul, Minn., 171–175.
- Keren, R., and Bingham, F. T. (1985). "Boron in water, soils, and plants." *Adv. Soil Sci.*, Vol. I, R. Stuart, ed., Springer-Verlag, Inc., New York, 229–276.
- Koyro, H.-W. (2003). "Study of potential cash crop halophytes by a quick check system: Determination of the threshold of salinity tolerance and the ecophysiological demands," in *Cash crop halophytes: Recent studies*, H. Lieth and M. Mochtchenko, eds., Kluwer Academic Publishers, Norwell, Mass., 5–17.
- Krauss, S., Schnitzer, W. H., Grassman, J., and Voitke, M. (2006). "The influence of different electrical conductivity values in simplified recirculating soilless

- system on inner and outer fruit quality characteristics of tomato." *J. Agric. Food Chem.*, 54, 441–448.
- Läuchli, A. (1984). "Salt exclusion: An adaptation of legumes for crops and pastures under saline conditions," in *Salinity tolerance in plants: Strategies for crop improvement*, R. C. Staples and G. H. Toenniessen, eds., John Wiley and Sons, Inc., New York, 171–187.
- . (1993). "Selenium in plants: Uptake, functions, and environmental toxicity." *Bot. Acta*, 106, 455–468.
- Levin, A. G., Lavee, S., and Tsrur (Lahkim), L. (2007). "The influence of salinity on *Verticillium dahliae* in stem cuttings of five olive cultivars." *J. Phytopath.*, 155, 587–592.
- Lieth, J. H., and Burger, D. W. (1989). "Growth of chrysanthemum using an irrigation system controlled by soil moisture tension." *J. Am. Soc. Hort. Sci.*, 114, 387–392.
- Lieth, H., and Mochtchenko, M. (2003). *Cash crop halophytes: Recent studies*, Kluwer Academic Publishers, Boston.
- Lynch, J., and Läuchli, A. (1985). "Salt stress disturbs the calcium nutrition in barley (*Hordeum vulgare* L.)." *New Phytol.*, 99, 345–354.
- Maas, E. V. (1986). "Salt tolerance of plants." *Appl. Agric. Res.*, 1, 12–36.
- . (1993). "Salinity and citriculture." *Tree Physiol.*, 12, 195–219.
- Maas, E. V., and Grattan, S. R. (1999). *Crop yields as affected by salinity, agricultural drainage*, Agronomy Monograph No. 38, R. W. Skaggs and J. van Schilfhaarde, eds., ASA/CSSA/SSSA, Madison, Wisc., 55–108.
- Maas, E. V., and Grieve, C. M. (1987). "Sodium-induced calcium deficiency in salt-stressed corn." *Plant Cell Environ.*, 10, 559–564.
- . (1994). "Salt tolerance of plants at different growth stages," in *Proc., Int. Conf. Current Developments in Salinity and Drought Tolerance of Plants. January 7–11, 1990, Tando Jam, Pakistan*, 181–197.
- Maas, E. V., and Hoffman, G. J. (1977). "Crop salt tolerance: Current assessment." *J. Irrig. Drain. Div. ASCE*, 103, 115–134.
- MacDonald, J. D. (1982). "Effect of salinity stress on the development of phytophthora root rot of chrysanthemum." *Phytopathology*, 72, 214–219.
- Marcar, N. E., Guo, J., and Crawford, D. F. (1999). "Response of *Eucalyptus camaldulensis* Dehnh., *E. globulus* Lavill. ssp *globulus* and *E. grandis* W. Hill to excess boron and sodium chloride." *Plant Soil*, 208, 251–257.
- Meiri, A. (1984). "Plant response to salinity. Experimental methodology and application to the field," in *Soil salinity under irrigation*, I. Shainberg and J. Shalhevet, eds., Springer-Verlag Inc., New York, 284–297.
- Meiri, A., Shalhevet, J., Shimshi, D., and Tibor, M. (1982). "Irrigation of spring potatoes with saline water," in *Annual report, Agricultural Research Organization, Institute of Soils and Water, Volcani Center, Bet Dagan, Israel*.
- Mizrahi, Y., and Pasternak, D. (1985). "Effect of salinity on quality of various agricultural crops." *Plant Soil*, 89, 301–307.
- Mohammadi, A. H., Banihashemi, Z., and Maftoun, M. (2007). "Interaction between salinity stress and verticillium wilt disease in three pistachio rootstocks in a calcareous soil." *J. Plant Nutr.*, 30, 241–252.
- Munns, R., and Termaat, A. (1986). "Whole-plant responses to salinity." *Aust. J. Plant Physiol.*, 13, 143–160.

- Nable, R. O., Bañuelos, G. S., and Paul, J. G., (1997). "Boron toxicity." *Plant Soil*, 193, 181–198.
- Navarro, J. M., Botella, M. A., and Martinez, V. (1999). "Yield and fruit quality of melon plants grown under saline conditions in relation to phosphate and calcium nutrition." *J. Hort. Sci. Biotech.*, 74, 573–578.
- Nicholaichuk, W., Leyshon, A. J., Jaime, Y. W., and. Campbell, C. A. (1988). "Boron and salinity survey of irrigation projects and the boron adsorption characteristics of some Saskatchewan soils." *Can. J. Soil Sci.*, 68, 77–90.
- Oertli, J. J., and Kohl, H. C. (1961). "Some considerations about the tolerance of various plant species to excessive supplies of boron." *Soil Sci.*, 92, 243–247.
- Ojala, J. C., Jarrell, W. M., Menge, J. A., and Johnson, E. L. V. (1983). "Influence of mycorrhizal fungi on the mineral nutrition and yield of onion in saline soil." *Agron. J.*, 75, 255–259.
- Oster, J. D., Hoffman, G. J., and Robinson F. E. (1984). "Management alternatives: Crop, water, and soil." *Calif. Agric.*, 38, 29–32.
- Page, A. L., Chang, A. C., and Adriano, D. C. (1990). "Deficiencies and toxicities of trace elements," in *Agricultural salinity assessment and management*, K. K. Tanji, ed., ASCE Manuals and Reports on Engineering Practice No. 71, ASCE, Reston, Va., 138–160.
- Parker, M. B., Gascho, G. J., and Gaines, T. P. (1983). "Chloride toxicity of soybeans grown on Atlantic coast flatwoods soils." *Agron. J.*, 75, 439–442.
- Parra, M. A., and Romero, G. C. (1980). "On the dependence of salt tolerance of beans (*Phaseolus vulgaris* L.) on soil water matric potential." *Plant Soil*, 56, 3–16.
- Pasternak, D., and De Malach, Y. (1994). "Crop irrigation with saline water," in *Handbook of plant and crop stress*, M. Pessarakli, ed., Marcel Dekker, Inc., New York, 599–622.
- Pasternak, D., Twersky, M., and De Malach, Y. (1979). "Salt resistance in agricultural crops," in *Stress physiology in crop plants*, H. Mussel and R. S. Staples, eds., John Wiley and Sons, New York, 128–152.
- Pearson, G. A. (1959). "Factors influencing salinity of submerged soils and growth of caloro rice." *Soil Sci.*, 87, 198–206.
- Poss, J. A., Pond, E., Menge, J. A., and Jarrell, W. M. (1985). "Effect of salinity on mycorrhizal onion and tomato in soil with and without additional phosphate." *Plant Soil*, 88, 307–319.
- Pratt, P. F., and Suarez, D. L. (1990). "Irrigation water quality assessments," in *Agricultural salinity assessment and management*, K. K. Tanji, ed., ASCE Manuals and Reports on Engineering Practice No. 71, ASCE, Reston, Va., 220–236.
- Ravikovitch, S., and Yoles, D. (1971). "The influence of phosphorus and nitrogen on millet and clover growing in soils affected by salinity. I. Plant development." *Plant Soil*, 35, 555–567.
- Ray, A. M., and Inouye, R. S. (2007). "Development of vegetation in a constructed wetland receiving irrigation return flows." *Agric. Ecosys. Environ.*, 121, 401–406.
- Rhoades, J. D., Bingham, F. T., Letey, J., Dedrick, A. R. (1988). "Reuse of drainage water for irrigation: Results of Imperial Valley Study. I. Hypothesis, experimental procedures and cropping results." *Hilgardia*, 56, 1–16.
- Rhoades, J. D., Bingham, F. T., Letey, J., Hoffman, G. J., Dedrick, A. R., Pinter, P. J., and Replogle, J. A. (1989). "Use of saline drainage water for irrigation: Imperial Valley study." *Agric. Water Mgmt.*, 16, 25–36.

- Ruiz-Lozano, J. M., Azcon, R., and Gomez, M. (1996). "Alleviation of salt stress by arbuscular-mycorrhizal *Glomus* species in *Lactuca sativa* plants." *Physiol. Plant*, 98, 767-772.
- Salisbury, F. B. (1995). *Units, symbols, and terminology for plant physiology*, Utah State University, Logan, Utah.
- Sannazzaro, A. I., Ruiz, O. A., Alberto, E. O., and Menendez, A. B. (2006). "Alleviation of salt stress in *Lotus glaber* by *Glomus intraradices*." *Plant Soil*, 285, 279-287.
- Sanogo, S. (2004). "Response of chili pepper to *Phytophthora capsici* in relation to soil salinity." *Plant Dis.*, 88, 205-209.
- Sarooshi, R. A., and Cresswell, G. C. (1994). "Effects of hydroponic solution composition, electrical conductivity and plant spacing on yield and quality of strawberries." *Aust. J. Exp. Agric.*, 34, 529-535.
- Sauer, M. R. (1968). "Effects of vine rootstocks on Cl concentration in Sultana scions." *Vitis*, 7, 223-226.
- Shalhevet, J. (1984). "Management of irrigation with brackish water," in *Soil salinity under irrigation: Processes and management*, I. Shainberg and J. Shalhevet, eds., Springer-Verlag, New York, 298-318.
- Shalhevet, J., Heuer, B., and Meiri, A. (1982). "Irrigation interval as a factor in the salt tolerance of eggplant." *Irrig. Sci.*, 4, 83-93.
- Shalhevet, J., Vinten, A., and Meiri, A. (1986). "Irrigation interval as a factor in sweet corn response to salinity." *Agron. J.*, 78, 539-545.
- Shannon, M. C., and Francois, L. E. (1978). "Salt tolerance of three muskmelon cultivars." *J. Am. Soc. Hort. Sci.*, 103, 127-130.
- Sharpley, A. N., Meisinger, J. J., Power, J. F., and Suarez, D. L. (1992). "Root extraction of nutrients associated with long-term soil management," in *Advances in soil science. Limitations to plant root growth*, Vol. 19, J. I. Hatfield and B. A. Stewart, eds., Springer-Verlag, New York, 151-217.
- Shear, C. B. (1975). "Calcium-related disorders in fruits and vegetables." *Hort. Sci.*, 10, 361-365.
- Shennan, C., Grattan, S. R., May, D. N., Hillhouse, C. J., Schachtman, D. P., Wender, M., Roberts, B., Tafoya, S., Burau, R. G., McNeish, C., and Zelinski, L. (1995). "Feasibility of cyclic reuse of saline drainage in a tomato-cotton rotation." *J. Environ. Qual.*, 24, 476-486.
- Shillo, R., Ding, M., Pasternak, D., and Zaccai, M. (2002). "Cultivation of cut flower and bulb species with saline water." *Sci. Hort.*, 92, 41-54.
- Sifola, M. I., De Pascale, S., and Romano, R. (1995). "Analysis of quality parameters in eggplant grown under saline water irrigation." *Acta Hort.*, 412, 176-184.
- Skaggs, R. W., and van Schilfgaarde, J. (1999). *Agricultural drainage*, ASA Monograph 38, ASA-CSA-SSSA, Madison, Wisc.
- Skaggs, T. H., Poss, J. A., Shouse, P. J., and Grieve, C. M. (2006a). "Irrigating forage crops with saline waters. I. Volumetric lysimeter studies." *Vadose Zone J.*, 5, 815-823.
- Skaggs, T. H., Shouse, P. J., and Poss, J. A. (2006b). "Irrigating forage crops with saline drainage waters. II. Modeling drainage and root water uptake." *Vadose Zone J.*, 5, 824-837.

- Smith, T. E., Grattan, S. R., Grieve, C. M., Poss, J. A., and Suarez, D. L. (2010a). "Salinity's influence on boron toxicity in broccoli. I: Impacts on yield, biomass distribution, and water use." *Agric. Water Mgmt.*, 97, 777–782.
- . (2010b). "Salinity's influence on boron toxicity in broccoli. II: Impacts on boron uptake, uptake mechanisms and tissue ion relations." *Agric. Water Mgmt.*, 97, 783–791.
- Snapp, S. S., and Shennan, C. (1992). "Effects of salinity on root growth and death dynamics of tomato, *Lycopersicon esculentum* Mill." *New Phytol.*, 121, 71–79.
- Snapp, S. S., Shennan, C., and van Bruggen, A. H. C. (1991). "Effects of salinity on severity of infection by *Phytophthora parasitica* Dast. ion concentrations and growth of tomato, *Lycopersicon esculentum* Mill." *New Phytol.*, 119, 275–284.
- Sonneveld, C. (1988). "The salt tolerance of greenhouse crops." *Neth. J. Agric. Sci.*, 36, 63–73.
- Steppuhn, H., van Genuchten, M. T., and Grieve, C. M. (2005a). "Root-zone salinity: I. Selecting a product yield index and response function for crop salt tolerance." *Crop Sci.*, 45, 209–220.
- . (2005b). "Root-zone salinity: II. Indices for tolerance in agricultural crops." *Crop Sci.*, 45, 221–232.
- Steppuhn, D., Wall, K. G., and P. G. Jefferson. (2009). "Seed size effects on emergence, height growth, and shoot biomass of first-year alfalfa grown in saline media." *Trans. Agri. Biol. Eng.*, 52, 121–132.
- Suarez, D. L., and Grieve, C. M. (1988). "Predicting cation ratios in corn from saline solution composition." *J. Exp. Bot.*, 39, 605–612.
- Suarez, D. L., Grieve, C. M., and Poss, J. A. (2003). "Irrigation method affects selenium accumulation in forage Brassica species." *J. Plant Nutr.*, 26(1), 191–201.
- Supanjani, K. D. L. (2006). "Hot pepper response to interactive effects of salinity and boron." *Plant Soil Environ.*, 52, 227–233.
- Tanji, K. K. (2007). "Salt management guide. Guide for landscape irrigation with recycled water in coastal southern California," CD database available from California Department of Water Resources, www.water.ca.gov, accessed February 12, 2011.
- Trajkova, F., Papadantonakis, N., and Savvas, D. (2006). "Comparative effects of NaCl and CaCl₂ on cucumber grown in a closed hydroponic system." *Hort. Sci.*, 41, 437–441.
- Triky-Dotan, S., Yermiyahu, U., Katan, J., and Gamliel, A. (2005). "Development of crown and root rot disease of tomato under irrigation with saline water." *Phytopathology*, 95, 1438–1444.
- Tripler, E., Ben-Gal, A., and Shani, U. (2007). "Consequence of salinity and excess boron on growth, evapotranspiration and ion uptake in date palm (*Phoenix dactylifera* L., cv. Medjool)." *Plant Soil*, 297, 147–155.
- Ungar, I. A. (1998). "Are biotic factors significant in influencing the distribution of halophytes in saline habitats?" *Bot. Rev.*, 64, 176–199.
- U.S. Salinity Laboratory Staff (USSL). (1954). *Diagnosis and improvement of saline and alkaline soils*, USDA Agricultural Handbook 60, USDA-ARS, Washington, D.C.

- van Genuchten, M. T. (1983). *Analyzing crop salt tolerance data. Model description and user's manual*, USDA-ARS/U.S. Salinity Laboratory Research Report No. 120, U.S. Government Printing Office, Washington, D.C.
- van Genuchten, M. T., and Gupta, S. K. (1993). "A reassessment of the crop tolerance response function." *J. Indian Soc. Soil Sci.*, 41, 730–736.
- van Genuchten, M. T., and Hoffman, G. J. (1984). "Analysis of crop salt tolerance data," in *Soil salinity under irrigation: Processes and management: Ecology studies 51*, I. Shainberg and J. Shalhevet, eds., Springer-Verlag, New York, 258–271.
- van Schilfgaarde, J. (1990). "Irrigated agriculture: Is it sustainable?" in *Agricultural salinity assessment and management*, K. K. Tanji, ed., ASCE Manuals and Reports of Engineering Practice No. 71, ASCE, Reston, Va., 584–595.
- Wadleigh, C. H., and Ayers, A. D. (1945). "Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration." *Plant Physiol.*, 20, 106–132.
- Wang, D. (2002). "Dynamics of soil water and temperatures in above ground sand cultures used for screening plant salt tolerance." *SSSA J.*, 66, 1484–1491.
- Wang, D., Grieve, C. M., and Suarez, D. L. (2005). "Composition of irrigation water salinity affects growth characteristics and uptake of selenium and salt ions by soybean." *J. Plant Nutr.*, 28, 1073–1088.
- Wang, D., Shannon, M. C., Grieve, C. M., Shouse, P. J., and Suarez, D. L. (2002). "Ion partitioning among soil and plant components under drip, furrow, and sprinkler irrigation regimes: Field and modeling assessments." *J. Environ. Qual.*, 31, 1684–1693.
- Wimmer, M. A., Mühling, K. H., Läuchli, A., Brown, P. H., and Goldbach, H. E. (2003). "The interaction between salinity and boron toxicity affects the subcellular distribution of ions and proteins in wheat leaves." *Plant Cell Environ.*, 26, 1267–1274.
- Wutscher, H. K., and Smith, P. F. (1996). "Citrus," in *Nutrient deficiencies and toxicities in crop plants*, W. F. Bennett, ed., American Phytopathology Society, St. Paul, Minn., 165–170.
- Yadav, H. D., Yadav, O. P., Dhankar, O. P., and Oswald, M. C. (1989). "Effect of Cl salinity and boron on germination, growth, and mineral composition of chickpea (*Cicer arietinum* L.)." *Ann. Arid Zone*, 28, 63–67.
- Yano-Melo, A. M., Saggin, O. J., and Mala, L. C. (2003). "Tolerance of mycorrhizal banana (*Musa* sp. cv. Pacovan) plantlets to saline stress." *Agric. Ecosys. Environ.*, 95, 343–348.
- Yermiyahu, U., Ben-Gal, A., Keren, R., and Reid, R. J. (2008). "Combined effect of salinity and excess boron on plant growth and yield." *Plant Soil*, 304, 73–87.
- Yermiyahu, U., Ben-Gal, A., and Sarig, P. (2006). "Boron toxicity in grapevine." *Hort. Sci.*, 41, 1698–1703.
- Yermiyahu, U., Ben-Gal, A., Sarig, P., and Zipilevitch, E. (2007). "Boron toxicity in grapevine (*Vitis vinifera* L.) in conjunction with salinity and rootstock effects." *J. Hort. Sci. Biotech.*, 82, 547–554.
- Zekri, M., and Parsons, L. R. (1990). "Comparative effects of NaCl and polyethylene glycol on root distribution, growth, and stomatal conductance of sour orange seedlings." *Plant Soil*, 129, 137–144.

NOTATION

C_{50} = soil salinity where crop yields are reduced 50%

EC = electrical conductivity of the irrigation water (EC_i), the soil water (EC_{sw}), and the saturated soil extract (EC_e)

EC_t = yield threshold soil salinity (EC_e) value (also referred to as the yield threshold "A" coefficient in other chapters) above which yields decline

p = coefficient that reflects the curve steepness and ST-index is salt-tolerance index